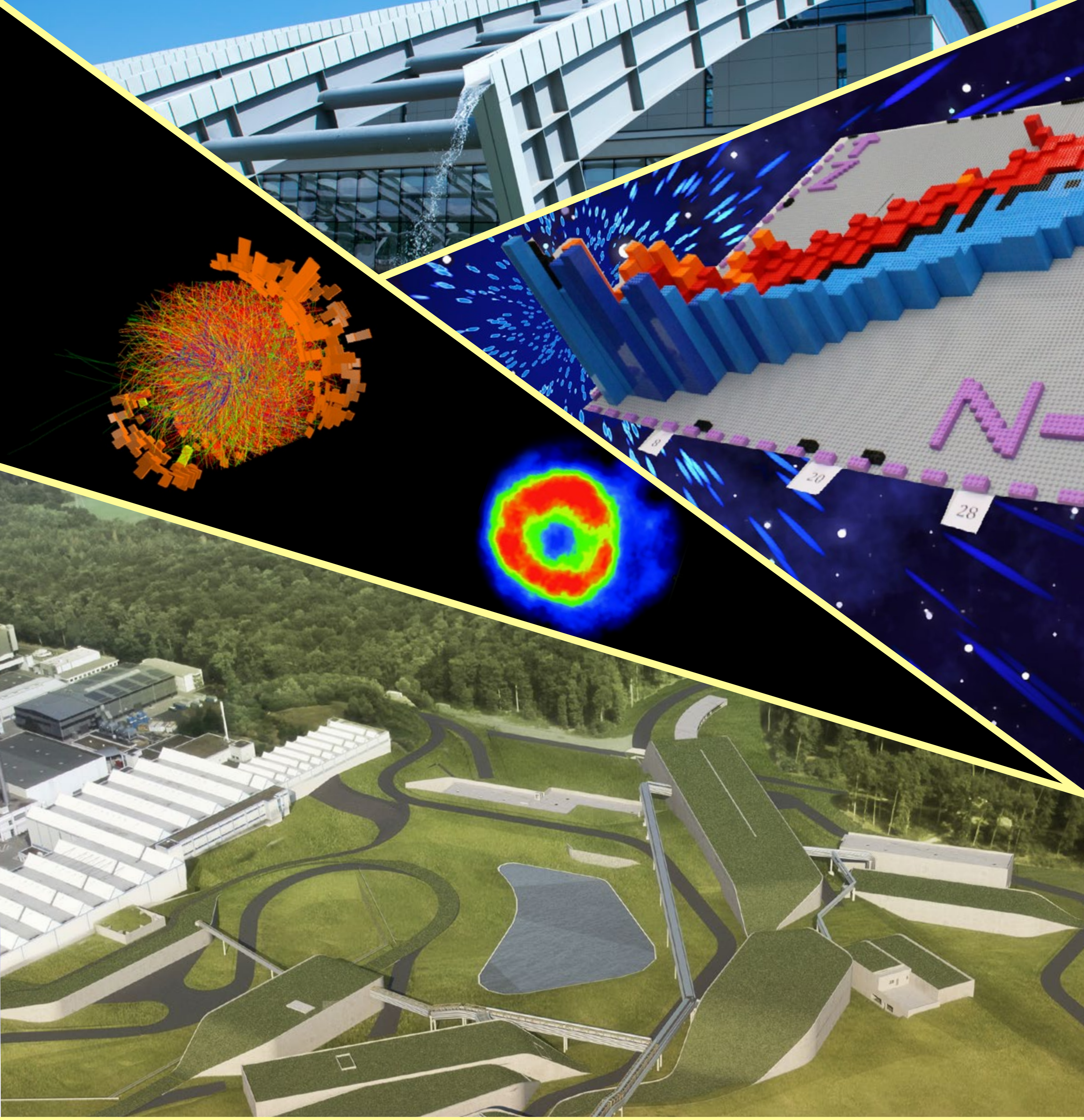

NuPECC

EUROPEAN SCIENCE FOUNDATION

NuPECC Long Range Plan 2017 Perspectives in Nuclear Physics

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eli nuclear physics

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FOREWORD

With this document NuPECC, the Nuclear Physics European Collaboration Committee, presents its Long Range Plan 2017. NuPECC's mission is "to provide advice and make recommendations on the development, organisation, and support of European nuclear research and of particular projects." To this aim, NuPECC has in the past produced four long-range plans (LRPs): in November 1991, December 1997, April 2004 and December 2010.

NuPECC in its October 2015 meeting at GANIL, Caen, France, initiated the process for the LRP 2017. It defined the subfields of nuclear physics to be addressed and established Working Groups spanning the areas of nuclear physics and its applications: Hadron Physics, Phases of Strongly Interacting Matter, Nuclear Structure and Dynamics, Nuclear Astrophysics, Symmetries and Fundamental Interaction as well as Applications and Societal Benefits. Two Conveners and three Liaison Members of NuPECC were assigned to each Working Group; their members selected to provide a broad representation of specific topics in the subfields. The Working Groups were given the charge to delineate the most exciting physics in their subfields, to highlight recent achievements, and to discuss the future perspectives. Draft reports from the Working Groups were presented and discussed at the NuPECC Meetings in 2016 at ECT* Trento in March, in Uppsala in June and finally in October in Vienna.

A Town Meeting to discuss the NuPECC LRP was held at the "darmstadtium" in Darmstadt, from January 11 – 13, 2017. Preceding the Town Meeting, preliminary reports of the Working Groups were posted on the NuPECC website. The Town Meeting was attended by almost 300 participants, including many young scientists. The programme contained sessions on future large scale facilities, the European and international context including presentations from NSAC (USA), ANPhA (Asia) and CERN and reports by the conveners of the Working Groups. The Town Meeting concluded with a general discussion. Following the Town Meeting, NuPECC discussed and finalized the recommendations in its meeting at CERN in March 2017. During this period, the Steering Committee's members, acting also as editors, implemented changes and suggestions from the community made during and following the Town Meeting. The result of this effort is the present report "NuPECC Long Range Plan 2017: Perspectives for Nuclear Physics".

After a short introduction, the report features the recommendations of NuPECC for the development of nuclear physics research in Europe followed by a comprehensive chapter on large and smaller facilities, existing, under construction or planned. The various reports of the Working Groups follow in the order: Hadron Physics, Phases of Strongly Interacting Matter, Nuclear Structure and Dynamics, Nuclear Astrophysics, Symmetries and Fundamental Interaction and Applications and Societal Benefits.

Europe has a leading position in nuclear physics research. It is through the collaborative effort of the European community that it can maintain such a position and advance it further. This Long Range Plan was established in a concerted action by the whole European nuclear physics community and its representative, NuPECC. It is strongly hoped that this plan will convince the European funding agencies to seek avenues for accomplishing the objectives outlined in the recommendations, in particular also those that go beyond the capabilities of an individual country.

Angela Bracco (NuPECC Chair)
for the NuPECC commitee

Gabriele-Elisabeth Körner
NuPECC Scientific Secretary

INTRODUCTION

SUMMARY AND RECOMMENDATIONS

The overarching goal of nuclear physics is to unravel the fundamental properties of nuclei from their building blocks, protons and neutrons, and ultimately to determine the emergent complexity in the realm of the strong interaction from the underlying quark and gluon degrees of freedom of Quantum Chromodynamics (QCD). This requires detailed knowledge of the structure of hadrons, the nature of the residual forces between nucleons resulting from their constituents and the limits of the existence of bound nuclei and ultimately of hadrons themselves. A thorough understanding is vital for the complex structure of nuclei, nuclear reactions, and the properties of strong-interaction matter under extreme conditions in astrophysical settings and in the laboratory. Nuclei also constitute a unique laboratory for a variety of investigations of fundamental physics, which in many cases are complementary to particle physics. Substantial experimental and theoretical efforts are being made world-wide to address the central questions of nuclear physics, which include:

- How is mass generated in QCD and what are the static and dynamical properties of hadrons?
- How does the strong force between nucleons emerge from the underlying quark-gluon structure?
- How does the complexity of nuclear structure arise from the interaction between nucleons?
- What are the limits of nuclear stability?
- How and where in the universe are the chemical elements produced?
- What are the properties of nuclei and strong-interaction matter as encountered shortly after the Big Bang, in catastrophic cosmic events, and in compact stellar objects?

These fascinating topics in basic science require concerted efforts in the development of new and increasingly sophisticated tools such as accelerators and detectors. It is important to emphasise that knowledge and technical progress in basic, curiosity-driven nuclear physics has significant societal benefits including the training of a highly skilled workforce and broad applications in industry, medicine, and security.

In the following a list of recommendations resulting from interaction and discussion with the community is presented.

Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

FAIR is a European flagship facility for the coming decades. This worldwide unique accelerator and experimental facility will allow for a large variety of unprecedented fore-front research in physics and applied sciences on both a microscopic and a cosmic scale. Its multi-faceted research will deepen our knowledge of how matter and complexity emerges from the fundamental building blocks of matter and the forces among them and will open a new era in the understanding of the evolution of our Universe and the origin of the elements.

- The Super-FRS together with storage cooler rings and the versatile NUSTAR instrumentation will allow decisive breakthroughs in the understanding of nuclear structure and nuclear astrophysics.
- The ultrarelativistic heavy-ion collision experiment CBM with its high rate capabilities permits the measurement of extremely rare probes that are essential for the understanding of strongly interacting matter at high densities.
- PANDA at the antiproton storage cooler ring HESR will provide a unique research environment for an extensive programme in hadron spectroscopy, hadron structure and hadronic interactions.
- APPA will exploit the large variety of ion beam species, together with the storage rings and precision ion traps, for a rich programme in fundamental interaction and applied sciences.

Support for construction, augmentation and exploitation of world leading ISOL facilities in Europe.

The urgent completion of the ESFRI facility SPIRAL2 along with SPES and the energy and intensity upgrade of HIE-ISOLDE (+ storage ring), including their unique instrumentation, will consolidate the leading role of Europe. These ISOL facilities with low energy and reaccelerated exotic beams, offer extraordinary opportunities for scientific discoveries to probe questions that concern the atomic nucleus and nuclei in the cosmos. The successful completion and exploitation of these facilities would be the major step toward the ultimate European ISOL facility, EURISOL. With this aim, a European collaborative initiative, the EURISOL- Distributed Facility, is strongly supported to maximize synergies to address and solve new scientific and technical challenges.

Support for the full exploitation of existing and emerging facilities

- The up-coming ESFRI facility ELI-NP with a worldwide unique gamma-beam quality and high power lasers will address key questions in nuclear structure, astrophysics and various applications. Completion of the facility and instrumentation is mandatory.
- For the up-coming NICA facility complete construction to study hot and baryon rich matter in heavy ion collisions at $\sqrt{s_{NN}}$ = 4 - 11 GeV. Develop and bring into operation the programme on BM@N, MPD and SPIN detectors as well as put into operation the SHE factory to search for a new stability regime for nuclei with Z beyond 118 (Og).
- Exploit the facilities DAΦNE, ELSA, GSI, MAMI and PSI for rich programmes on hadron interactions and on hot baryonic matter.
- Exploit the facilities ALTO, GANIL-SPIRAL2, GSI-FAIR, IFIN-HH/ELI-NP, ISOLDE, JYFL, KVI-CART, LNL-LNS, NLC Warsaw-Krakow, mainly devoted to nuclear structure, nuclear astrophyics, reactions and applications.
- Exploit the small scale existing facilities devoted to specific topics in nuclear physics and applications. Among them LUNA-MV@LNGS, nTOF@CERN, ELENA@CERN and NP@ILL are worldwide unique.

Support for ALICE and the heavy-ion programme at the LHC with the planned experimental upgrades.

The heavy-ion programme at the CERN Large Hadron Collider is uniquely suited to determine the properties of the Quark Gluon Plasma at high temperature. Progress relies on new and larger data samples, which are needed for more precise and differential measurements. The experimental programme aims to fully exploit the high-energy collisions which will be delivered by the LHC in Run-3 and Run-4. We consider it crucial that all aspects of the LHC heavy-ion programme, including manpower support and completion of the detector upgrades, are strongly supported.

Support to the completion of AGATA in full geometry

AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in the long-term must be fully completed in full 60 detector unit geometry in order to realise the envisaged scientific programme. AGATA will be realised in phases with the goal of completing the first phase with 20 units by 2020.

Support for Nuclear Theory

With continued major conceptual and computational advances, nuclear theory plays a crucial role in shaping existing experimental programmes. Combining theory initiatives in a concerted effort is essential for optimal use of the available resources, in particular by providing platforms for scientific exchange and the training of the next generation. At the same time it is important to increase the work force and to strengthen collaborations and accessibility in the area of high-performance computing.

With the emergence of a common European Research Area (ERA) and growing international cooperation, *ECT**, as a highly successful and unique centre for nuclear theory, faces new opportunities and challenges. The significant European and global investments in accelerator centers and other experimental facilities require coordinated theoretical efforts which are well served by ECT*. Given its past success and the high international visibility, continued operation and financial stability need to be ensured.

Nuclear theory is a significant driving force in the utilization of high-performance computing facilities at the national and European level. The planning of future high-performance installations is recognized as being of strategic importance for Europe. Being ready to exploit new computational capabilities efficiently in an early stage will be mandatory for the international competitiveness of European nuclear theory.

Perform vigorous programmes in nuclear applications

Nuclear Physicists are mobilised to answer fundamental needs and questions addressed by society specifically on energy, health, knowledge and protection.

- For nuclear energy systems the development of predictive and reliable models and simulation tools is mandatory. This implies a strong cooperation between experimentalists, theoreticians and evaluators. The DEMO-Oriented Neutron SOURCE (IFMIF/DONES) and the ADS demonstration project MYRRHA at SCK·CEN will be important in this domain.
- It is important to continue the development of adapted techniques for cancer treatment. In particular, efforts should be made for the production of specific radio-isotopes and more efficient imaging techniques in strong collaboration with the end-users.
- With the availability of high-intensity accelerators and new installations (GANIL, ESS, FAIR, ISOLDE) new studies in materials science, atomic and plasma physics will be possible, exploring matter in extreme conditions. Some of these installations will also be used to study and develop the production of new radioisotopes for medical use.

Perform R&D programmes for possible future facilities.

In order to lay the foundations for exciting new science opportunities in the long-term future, the respective communities must vigorously pursue coordinated research and development programmes, aiming at:

- the concept of (a) precision storage ring(s) to search for charged particle electric dipole moments (EDM), based on the ongoing studies at COSY;
- the design of a polariser ring to produce high intensity polarized antiproton beams as one upgrade option for HESR at FAIR;
- the implementation of sympathetic laser cooling techniques to cool systems like the proton, antiproton and highly charged ions to temperatures as low as a few mK;
- the design of advanced high intensity lasers for precision spectroscopy of exotic atoms, such as antihydrogen, muonic hydrogen, pionic helium, and muonium;
- the development of highly stable and well defined magnetic fields, both very high and very low, as well as accurate high precision magnetometry in connection with NMR techniques, required, e.g., in the quest for electric dipole moments and novel dark matter searches.

Training the next generation of nuclear scientists

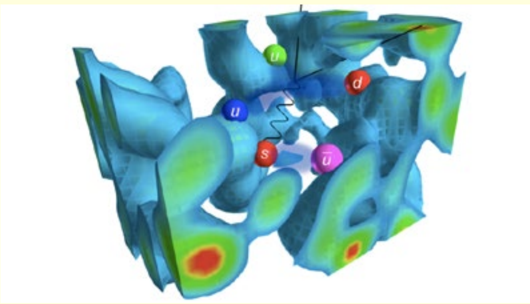
The community is vigorously pursuing a coordinated research and development programme for exciting new science opportunities, resulting in a wide spectrum of applications of nuclear technology and methods of great relevance to our everyday life. The importance of nuclear technology in nuclear medicine resulting in better imaging and tumor therapy techniques, in security, in materials studies with nuclear probes, etc. cannot be overstated.

It is therefore important to nurture and expand the highly qualified workforce trained in nuclear science as a very important element to maintain the development in the field. A sufficient number of PhD and postdoctoral researcher positions, attached to facilities as well as universities is required. The different roles that large and small scale facilities and universities can play in educating the next generation of nuclear scientists needs to be acknowledged, and specifically the role of the small-scale facilities and university labs in exposing young researchers to all aspects of a scientific project cannot be overestimated. The flanking programme of summer schools such as, the EUROSCHOOL and those in GSI and ECT* are also very important to give a broad overview of the field to young researchers.

THE SCIENCE

This long range plan has six chapters, each focusing on a particular topic in nuclear physics which are addressed by research in specific sub-fields. These chapters present the relevant achievements made in the last decade and discuss the urgent needs for research in the coming years. The working groups that have prepared these chapters, after consultations with other experts in their field, have also formulated a set of perspectives and recommendations which are specific of their sub-fields.

In this introduction chapter a short overview of the sub-fields is given which follows the sequence of the six chapters.



Pictorial view of a QCD calculation for the structure of the particle Lambda 1405 (from CSSM, University of Adelaide).

Hadron physics

Hadron physics is concerned with the study of the underlying structure and interactions of nuclear matter at the most fundamental level, that of quarks and gluons. Ultimately, the very existence of nuclei is due to the interactions of colour charged quarks and gluons, which are described by the theory of Quantum Chromo Dynamics (QCD). The theoretical description of the strong interaction has given rise to some of the most influential ideas in quantum field theory. In addition, QCD is one of the pillars of the Standard Model (SM) of particle physics. While QCD is well tested at high energies, where the strong coupling constant is sufficiently small for perturbation theory to apply, it becomes a strongly coupled theory in the low energy regime where many aspects await a better understanding.

Significant progress has been made over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated intense theoretical activity and a refinement of the theoretical tools. In spite of these developments, many fundamental questions concerning the structure and spectroscopy of hadrons remain unanswered. Furthermore, key issues such as the confinement of quarks or the existence of glueballs and hybrids are long-standing puzzles and present an intellectual challenge in our attempt to understand the nature of the strong interaction and of hadronic matter.

Experiments that test QCD use various probes to investigate different aspects of hadron spectroscopy, hadron structure and hadron dynamics. These experiments explore both the non-perturbative and perturbative regimes. High-momentum processes, such as Deep Inelastic Scattering probe the perturbative regime, in which the observables are directly related to the quark and gluon degrees of freedom of the QCD Lagrangian. In these processes the soft (non-perturbative) part of the amplitude gives access to key aspects of hadron structure, such as the spatial distribution of quarks in the proton, or the connection between the quark spin and orbital angular momentum and the spin of the proton.

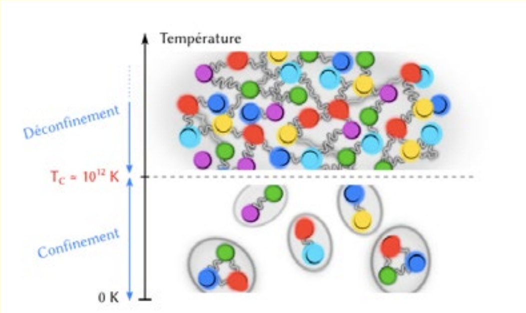
On the other hand, low-momentum processes explore QCD in the non-perturbative regime. Theoretical calculations can be carried out by means of computer simulations on a discretised space-time lattice (Lattice QCD) or using effective field theories based on hadronic degrees of freedom that respect the symmetries of QCD. A significant amount of additional experimental data is required to identify the relevant degrees of freedom. This is one of the main goals of hadron spectroscopy.

Understanding the physics of hadrons requires a large variety of complementary experiments and theoretical tools. In experiments, electromagnetic and hadronic probes can be used to study various aspects of hadron structure, spectroscopy and dynamics at different energy scales. These different experimental techniques provide complementary information, and it is of vital importance that all be pursued in order to obtain a complete picture and reach a full understanding of the field.

In the coming years Europe is in a unique position to play a central role with the antiproton programme at the FAIR facility under construction in Germany combined with programmes with polarised protons in Dubna and those with lepton and hadron beams (MAMI, Bonn, INFN-Frascati) at existing facilities. FAIR is expected to produce groundbreaking results and to provide a unique research environment for all aspects of hadron physics coming from experiments with antiprotons (PANDA). Tremendous theoretical progress has been achieved by lattice QCD and effective field theories, leading to ab-initio calculations of many hadronic properties. Of fundamental importance to the progress in hadron physics is the interplay between theory and experiment, which must continue in the future.

Properties of Strongly Interacting Matter at extreme conditions of temperature and baryon number density

The behaviour of the strength of QCD coupling, which decreases at short distances and increases at large distances (in contrast to Quantum Electrodynamics, where the coupling evolves in the opposite way), is the origin of two very peculiar features of the strong interaction: the asymptotic freedom and the colour confinement. As a consequence, neither quarks nor gluons exist as isolated particles in Nature, and the only stable arrangements are colour-singlet bound states, i.e., hadrons, which may either be mesons formed from quarks and antiquarks or (anti-)baryons formed from three (anti-)quarks.



Schematic illustration of the quark confinement in baryons and mesons and, at high temperature, the quark deconfinement

Asymptotic freedom has a very profound implication for hadronic matter under extreme conditions because at sufficiently high nuclear density or temperature, the average inter-parton distance becomes small, and therefore their interaction strength weakens. Above a critical energy density, of the order of 0.3 GeV/fm^3, a gas of hadrons undergoes a deconfinement transition and becomes a system of unbounded quarks and gluons, the so-called quark-gluon plasma (QGP). Numerical evidence of this transition has been obtained from lattice simulations of QCD, in the form of a rapid increase of the entropy density around the critical energy density. The formation of QGP is accompanied by a restoration of chiral symmetry, spontaneously broken in the QCD vacuum.

QGP occurred in the very early Universe, a few microseconds after the Big Bang, and it is believed existing inside the core of neutron stars, at baryon densities much higher than normal nuclear densities.

The transition between the primordial QGP and the hadron formation has, as far as we know, not left any imprint that is visible in present-day astronomical observations. However, the energy or baryon densities necessary to form the QGP may be recreated in the laboratory via heavy ion collisions at sufficiently high energies, within volumes of the order of the nuclear size.

Several facilities in Europe are currently operating, in construction or in discussion, to provide heavy-ion collisions at various energies, with the aim to explore different regions of the phase diagram of QCD.

The LHC at CERN has delivered Pb beams since 2010 and has reached the record energy of 5.02 TeV in the Pb-Pb center of mass. From 2021, the LHC will operate at the nominal center-of-mass energy of 14 TeV for proton-proton and of 5.5 TeV per nucleon pair in PbPb collisions, and will make a significant step forward in the luminosity. The long shutdown LS3 will prepare the machine and the experiments to a further jump of a factor 10 in proton-proton luminosity, with the High-Luminosity LHC entering operation in 2026 with two runs presently foreseen (Run-4 and Run-5). Further plans are under study at CERN for future heavy-ion initiatives (NA60+ at the SPS, AFTER at the LHC, the Future Circular Collider).

Among the facilities in construction, FAIR and NICA feature approved heavy ion programmes, which at FAIR will be conducted by the high-rate experiment CBM (Compressed Baryonic Matter) being designed to observe rare probes and to operate at SIS-100, with well-defined upgrade options for a possible later use at higher energies, and the HADES detector, which is currently in operation at the SIS-18 accelerator at GSI and which will be moved to the SIS-100 beam line.

At NICA, the BM@N and MPD experiments will study the hot and dense nuclear matter at a

centre-of-mass energies ranging from 4 to 11 GeV per nucleon with an average luminosity in the collider mode of $1{\cdot}10^{27}$ cm^{-2} s^{-1} for Au^{79+} collisions.

Nuclear Structure and Reaction Dynamics

The strong interaction described by quantum chromodynamics is responsible for binding neutrons and protons into nuclei and for the many facets of nuclear structure and reaction physics. Combined with the electroweak interaction, it determines the properties of all nuclei in a similar way as quantum electrodynamics shapes the periodic table of elements. While the latter is well understood, it is still unclear how the nuclear chart emerges from the underlying strong interactions. This requires the development of a unified description of all nuclei based on systematic theories of strong interactions at low energies, advanced few- and many-body methods, as well as a consistent description of nuclear reactions. In this sub-field of Nuclear Physics a number of key questions will be addressed such as:

- How does the nuclear chart emerge from fundamental interactions?
- Where are the limits of stability and what is the heaviest element?
- How does nuclear structure evolve across the nuclear landscape and what shapes can nuclei adopt?
- How does the structure change with temperature and angular momentum?
- How to unify nuclear structure and reaction approaches?
- How complex are nuclear excitations?

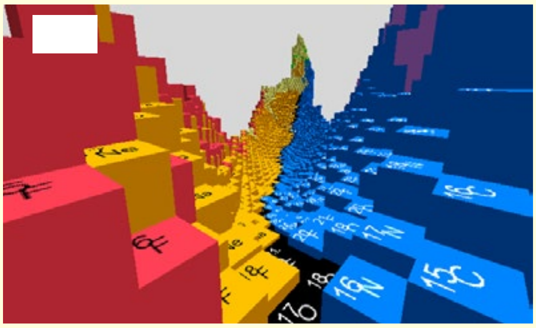


Illustration of the valley of stability within the nuclear chart. Stable nuclei (black) are the most tightly bound, whereas nuclei with proton or neutron excess are unstable. (Image: CSNSM Orsay)

- How do correlations appear in dilute neutron matter, both in structure and reactions?
- What is the density and isospin dependence of the nuclear equation of state?

Nuclear structure and dynamics have not only reached the discovery frontier (e.g. focused on new isotopes, new elements, etc.), but is also entering into a high precision regime with higher beam intensities and purity, along with better efficiency and sensitivity of instruments, in order to focus on essential observables to validate and guide our theoretical developments.

These developments are closely connected to the existing and new high-intensity stable and radioactive ion beam facilities in Europe, the latter especially conceived to study the structure of exotic nuclei. For instance, the study of nuclear ground- and excited-state properties is vital in revealing the role played by the strong interaction in atomic nuclei and in understanding nuclear structure phenomena and their emergence from fundamental interactions. FAIR, with the Super Fragment Separator and its storage rings, offers unique opportunities for properties and phemomena of exotic nuclei far off stability, in particular giving access to nuclei forming the third peak in abundances of elements due to the r-process.

The low-energy ISOL facilities HIE-ISOLDE, SPES and SPIRAL2 will provide a new generation of re-accelerated radioactive ion beams. They are being developed and their construction should be vigorously pursued to start the exciting physics programmes in the coming decades.

Stable beam facilities will continue to perform vital science programmes in the study of exotic nuclei at the extremes of isospin, angular momentum and temperature. In addition, the structure of the heaviest elements will be further explored with new accelerators for high-intensity stable beams at JYFL, GSI, GANIL-SPIRAL2 and JINR-SuperHeavy Elements Factory. The brilliant gamma beams from ELI-NP will open up new perspectives using electromagnetic probes, complementary to the other nuclear physics research facilities. Finally, breakthrough research in theoretical nuclear physics relies on continued access to national and European high-performance computing facilities with leading edge capabilities.

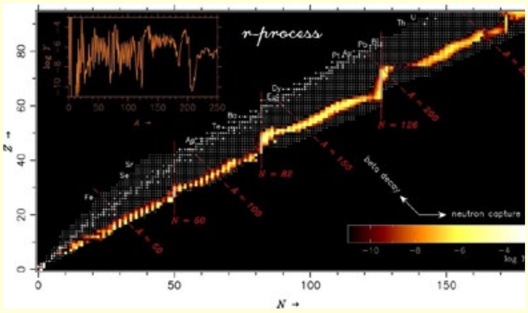
Nuclear astrophysics

The world around us is intimately linked with the properties and reactions of atomic nuclei. From the lives and deaths of stars, to the evolution of the Galaxy, it is Nuclear Physics that has shaped the Universe, linking processes that operate at femtometer scales to structures that stretch across thousands of light years. Nuclear astrophysics is the field that brings together different scientific disciplines to answer some of the key questions about the Universe. The challenge of understanding the origin and evolution of the chemical elements, and the role of Nuclear Physics in the lives and deaths of stars, requires state-of-the-art experimental, theoretical and observational capabilities. Nature has supplied the Earth with about 300 stable as well as long-lived radioactive isotopes that we can study in the laboratory. However, a much greater variety of (mostly unstable) isotopes is produced during stellar explosions. Radioactive beam accelerator facilities provide access to an increasing number of these exotic nuclei. With current and future generations of facilities, we can study the properties of and reactions among these rare isotopes, to give insight to the nuclear processes that synthesise elements.

The nuclear properties relevant for the description of astrophysical processes depend on the environmental conditions. Nuclear theory is fundamental to connect experimental data with the finite temperature and high density conditions in the stellar plasma. Advances in the description of nuclear interactions based on the symmetries of quantum chromodynamics, together with novel many-body techniques, allow for parameter-free calculations of reactions relevant for stellar burning. Microscopic approaches from light toward heavy nuclei will allow for theoretical predictions with uncertainty estimates relevant for the description of explosive scenarios.

Nuclear physics is crucial for our understanding of the evolution and explosion of stars, the chemical evolution of the Galaxy and its assembly history. It contributes to key science question such as:

- What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?
- Where are the building blocks of life created?



Calculated abundance distribution of nuclides during r-process nucleosynthesis (S. Wanajo et al. Astrophys. J. 606 (2004) 1057)

- How do nucleosynthesis processes evolve with time?

Due to the great diversity and strong interdisciplinary character of the field, nuclear astrophysics requires a wide range of experimental facilities, from major international laboratories to smaller university-based centres. The small scale facility LUNA with the new multi-MV accelerator and associated infrastructure, will allow for access to a new range of nuclear reactions.

Many large-scale European nuclear physics facilities maintain a strong research programme in nuclear astrophysics and make important contributions to our understanding of explosive astrophysical environments.

FAIR with its storage rings and its instrumentation of all experimental pillars will open up broad and exciting perspectives for nuclear astrophysics. The NUSTAR Collaboration will exploit the unparalleled access to unstable nuclei far from stability, in particular to the heavy neutron-rich r-process nuclei around N=126. CBM will study the properties of matter at the high densities achieved in neutron stars and will constrain the supernova equation of state. With its ability to produce high rates of hypernuclei PANDA will contribute to our understanding of the nucleon-hyperon and NN-hyperon interactions. The APPA collaboration will explore the behaviour of matter, in storage ring experiments, under the extreme electromagnetic fields achieved on neutron star surfaces and, in ion-beam and laser experiments under the astrophysical conditions expected in stellar plasma and in gaseous planets.

The next generation of radioactive ion beam facilities, including HIE-ISOLDE, SPES-INFN and SPIRAL2 (leading to EURISOL-DF) will enable the study of reactions of astrophysical importance. This programme will in particular benefit from the installation of a storage ring at HIE-ISOLDE.

The ELI-NP facility will provide high-power laser pulses and high-intensity narrow-bandwidth gamma beams. Studies of laser-driven nuclear reactions in controlled plasma conditions will become possible together with measurements on photodissociation reactions with unprecedented precision. This will provide new research opportunities for the nuclear astrophysics community in Europe.

Symmetries and Fundamental interactions

The presently known fundamental interactions governing Nature and the Universe from the largest to the smallest distances display symmetries and symmetry breaking. High precision studies allow tests of our understanding of Nature that are complementary to experiments at the highest energies and sometimes offer higher sensitivities to new effects beyond the Standard Model (SM) of particle physics.

Nuclear Physics has played a major role in finding and establishing the laws which govern the physics at the most fundamental level. One of the most notable examples is the maximal violation of spatial inversion symmetry, parity P, in the weak interaction. Shortly after the discovery of P violation also the combined CP symmetry (P and charge conjugation C) was found to be broken. These discoveries have triggered intense research on symmetry violations, including those of time reversal (T) symmetry. In Quantum Field Theory (QFT) C, P, and T are related by the CPT invariance theorem resting among other assumptions on Lorentz Invariance. Experimental activities include parity violation studies on atoms, ions and molecules and searches fo time reversal violating electric dipole moments (EDMs) of particles. High precision CPT tests with low energy anti-protons are conducted at AD/ELENA and in the future at FAIR.

Today, fundamental physics is a field bridging the areas of nuclear, atomiFFc, particle and astrophysics. Major advances in state-of-the-art technology have made novel approaches feasible. The most accurate technologies from various research fields are employed to prepare the fundamental systems under study. They range from low-energy particles, ultracold atoms, ions and molecules (with major applications also in chemistry, quantum information processing and metrology), through novel sensors and radiation detectors (also used for medical applications), to the analysis of complex sets of data and extracting the underlying information (e.g. big data, computing, pattern recognition, ...). At the same time the most advanced theoretical and calculational techniques are developed and applied by nuclear, atomic and particle theory

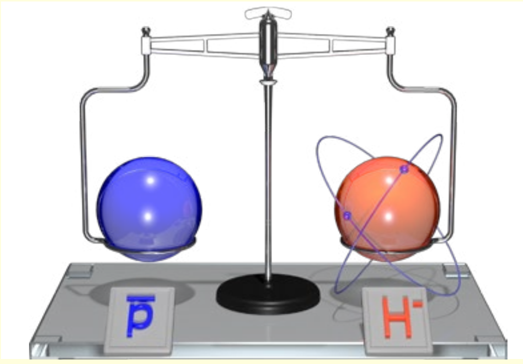


Illustration of the comparison of the gravitational mass of an antiproton and a proton, which was obtained by comparing the cyclotron frequency of an antiproton and a H^- ion in a Penning trap. Image: Georg Schneider, BASE collaboration

to perform ever more stringent comparisons between theory and observation, and to establish discrepancies. While nuclear and particle physics have developed along different pathways, technologies have usually been shared. We find today, in particular also from high energy particle physics, an increasing interest in complementary approaches to the same most fundamental questions and a growing appreciation for key experiments in the intensity and precision physics domain sometimes sensitive to high energy and mass scales exceeding those for the present and future collider experiments. Nuclear Physics and its technologies play crucial roles in many such experiments. Theory is about to develop common languages, for example in the form of the Standard Model Effective Field Theory, which can systematically parametrise any new physics at high energy scales and connect experiments at different energy scales. The research in the field proceeds along two main routes: precision determinations of fundamental parameters and searches for deviations from the SM predictions. Precision measurements of, for example, masses, mixings and coupling constants, are ideally carried out in complementary approaches to allow overdetermination of theory parameters and cross-checks.

With improved experimental precision, sensitivity and stability, long-duration observations can be turned into searches and tackle the question of time dependence of fundamental "constants", the constancy of which is often taken for granted. Another class of sensitive searches can be performed where the predicted value of an observable is negligibly small or even zero in the standard theory. Examples include permanent electric dipole moments (EDM) of particles, which are performed in university laboratories, at the radioactive ion beam facilities e.g. ISOLDE and LNL for unstable nuclei, and with neutrons at large facilities like ILL, FRM-II, PSI and in the future ESS. Further examples are neutrinoless double beta decay (done in underground laboratories LNGS, Modane and Canfrac), and charged-lepton flavour violation studied in Europe with muons at PSI.

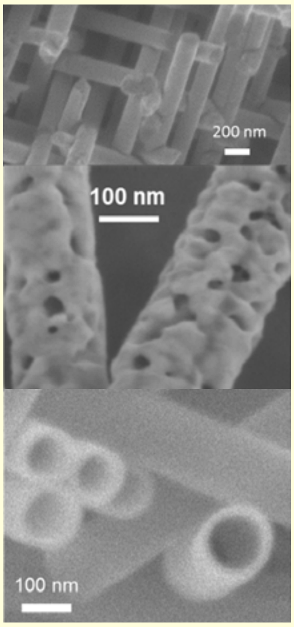
Many of the precision experiments to study fundamental interactions require dedicated table-top setups in small-size laboratories at universities where innovative techniques are tested before they get installed at larger online facilities and large-scale infrastructures (at the ones listed above as well as at other radioactive beam facilities like GSI/FAIR, GANIL and IGISOL, in storage rings at GSI/FAIR, using electron scattering at MESA and kaonic atoms at DAΦNE).

Applications and societal benefits

Applications derived from basic Nuclear Physics Research have a large impact on many aspects of everyday life. Society benefits from the large investments done in basic Nuclear Physics research in areas as diverse as nuclear medicine, energy, nuclear stewardship and security. Recent achievements in particle- and radio-therapy within the new paradigm of a theranostic approach are but some of the most striking examples of the benefits from Nuclear Physics.

Improvements in nuclear applications were obtained thanks to an increase of the basic knowledge on nuclear structure and decay, nuclear reactions and nuclear system properties but also thanks to the developments in related technologies, such as accelerator science, instrumentation and high-performance computing. The Nuclear Physics community continues to build on its strong track record to answer fundamental societal needs specifically on energy, health and security. This has led to a new transverse discipline of Applied Nuclear Physics research.

Reliable, up-to-date and well-structured data libraries are indispensable both for Applied and Fundamental Nuclear Physics research. The ability to develop and maintain a high level of expertise in the area of nuclear data to meet the data needs of a continuously developing European Nuclear Physics landscape is a key issue that needs to be addressed by the European Nuclear Physics community as a whole.



Novel ion-track technology based nanostructures such as nanowire networks (top), porous wires (center) and nanotubes (bottom) with tailored diameter, length and surface.

THEORY AND COMPUTING

Nuclear theory is making major conceptual and computational advances that address the fundamental questions of the field. The theoretical tools have matured such that they begin to span the strong interaction landscape from the elementary constituents, quarks and gluons, as the building blocks for the computation of hadrons and nuclei to the computation of the equation of state for infinite nuclear matter and neutron star matter. In all areas of theoretical nuclear physics algorithmic and computational advances thus hold promise for breakthroughs in predictive power including proper error estimates.

Accompanying the experimental developments, qualitative changes in the theoretical understanding of strong interaction (QCD) matter have taken place. Lattice simulations of QCD thermodynamics have entered the precision era. Similarly, lattice studies of hadron structure and spectroscopy have led to major advances on a quantitative level. Effective field theories rooted in QCD are used to describe properties of light nuclei and for ab initio many-body predictions.

As detailed throughout this document, nuclear theory plays a crucial role in shaping existing experimental programmes in Europe and provides guidance to new initiatives in nuclear physics. Combining theory initiatives in a concerted effort is essential for optimal use of the available resources, in particular by providing platforms for scientific exchange and the training of the next generation of nuclear theorists. At the same time it is important to strengthen collaborations and accessibility in the area of high-performance computing (HPC).

EDUCATION

The big bang, the fuel of stars and supernovae, the source of power to run our homes and factories; these are all examples of how nuclear physics plays an important role in understanding the Universe around us. The nucleus is a unique laboratory in which the interplay between the fundamental forces can be studied in detail. The next few years, driven by experimental and theoretical advances, will see a revolution in our understanding of the quantum world that is the nucleus. The advent of many new facilities will allow an unprecedented number of new nuclei to be studied with their properties giving us a new insight across the whole chart of nuclei from light to heavy nuclei. It is vital that there is an education programme to ensure that the new nuclear physicists of the future are ready to take on the challenge.

An important aspect of education and training in nuclear physics is the PhD (or DPhil) doctoral degree. Nuclear Scientists are also involved with delivering education programmes at master's level specifically tailored for those who are seeking a career in nuclear related industries and for those already in industry who are developing their careers and skills.

Nuclear Physics researchers also provide input to outreach activities targeted at the key school age audience, 11-18 as well as the wider public. These interactions bring nuclear physics to wide range of people through for example:

- Public talks at local science societies
- Exhibitions and open days at universities, national laboratories and those places more generally open to the public such as museums
- Web-based resources including games and teaching resources
- School talks, summer internships and work experience
- Undergraduate projects involving students in research

These activities are essential for inspiring and attracting young people to study STEM subjects and promoting Nuclear Physics. This in turn is essential to underpin the future workforce in the role of inspirational science.

NuPECC sponsors the NUPEX resource which can be found online at http://nupex.eu/. This provides information on Nuclear Physics suitable for a wider audience covering topics including the material world, nuclear energy and applications of Nuclear Physics and its techniques.

INTERNATIONAL CONTEXT

International collaboration both between European institutions and with those beyond the borders of Europe has always been a key part of European strategy and it has played a significant role in the success of research in all domains of nuclear physics.

Several projects funded by the European Commission , in particular those supporting Trans-National Access to several large scale facilities in Europe, have enhanced collaboration among different institutions in Europe and strengthened the ties and knowledge exchange among experts involved in new developments. The European Commission projects supporting open access to large facilities usually belong to "Integrated Activities" calls. Since the turn of the century, two major projects have been funded, one concerning research into hadron physics and the other mainly with nuclear structure studies and applications of nuclear physics. Within the current HORIZON2020 framework, the ENSAR2 project is active. The work of ENSAR2 is based around facilities devoted to nuclear structure studies. In addition, a new project for facilities for hadron physics is under preparation, representing a follow up of the previously successful project HP3. One important development is that now the European Commission is open to support funding for access in European facilities for non-European users through bi-lateral agreements with laboratories which in turn provide support to European users. The first agreement of this type was recently made within the ENSAR2 project with the Nishina Center in RIKEN (Japan).

Concerning the effort to organise project funding among different funding agencies, European support was received for the ERA-NET project NuPNET, resulting in the collection of common funding for detector and accelerator developments.

Since nuclear science is a worldwide endeavour, connections between the important players in the field are well established, but also being further developed and improved at all levels, through users, collaborations and expert committees.

Professor and student working on a laser setup used for the study of nuclear properties of radioactive ion beam

European researchers in experimental nuclear physics are very active in many laboratories such as RHIC, CEBAF, NSCL and ATLAS in USA, TRIUMF in Canada, BELLE, RIKEN and JPARC in Japan and BES in China. On the theory side, it is very important to underline the success in running worldwide activities at ECT* in Trento and INT in Seattle.

The European groups working at JLAB and COMPASS provide a very valuable contribution to the R&D for the EIC project which is expected to have a worldwide dimension. NuPECC highly recognizes the science of the EIC project, presently under study, representing an opportunity for a major step forward in the field of hadron physics.

NuPECC maintains regular contact with similar expert committees outside Europe, namely NSAC (USA), ANPhA (Asia), ALAFNA (Latin America) and NSERC (Canada). These contacts are based on reciprocal attendance of the chairs of these committees as observer in several meetings. In addition, NuPECC reports on its activity and programmes at the annual meetings of WG.9 of IUPAP. Its members come from Australia, Canada, China, France, Germany, India, Italy, Japan, Korea, Russia, South Africa, ALAFNA, AnPhA, NSAC, NuPECC.

Last, but not least, NuPECC participates as observer in the Physical Sciences and Engineering group of ESFRI and through its Long Range Plan can contribute to the process of preparing the report on the European Landscape of Research Infrastructures, a document released by ESFRI and regularly updated. The landscape analysis is an important document useful for the selection of facilities on the ESFRI list.

ENSAR2

In order to carry out research at the forefront of fundamental nuclear science, our community of nuclear scientists profits from the diverse range of large research infrastructures (RIs) existing in Europe. These RIs can supply different species of ion beams and energies but are complementary in their provision of beams and address different aspects of nuclear structure, nuclear reactions and nuclear astrophysics. In this way, we can learn how the nuclear forces arising from the interaction between the building blocks of neutrons and protons manifest themselves in the rich structure of nuclei, and how different isotopes of elements are synthesised in primeval stellar processes.

ENSAR2 is the Horizon-2020 integrating activity (IA) for European nuclear scientists who are performing research in three of the major subfields defined by

NuPECC: Nuclear Structure and Dynamics, Nuclear Astrophysics and Nuclear Physics Tools and Applications. It proposes an optimised ensemble of Networking (NAs), Joint Research (JRAs) and Transnational Access Activities (TAs), which will ensure qualitative and quantitative improvement of the access provided by the current ENSAR2 infrastructures. The novel and innovative developments that will be achieved by the RTD activities will also assure state-of-the-art technology needed for the new large-scale projects.

Transnational Access

ENSAR2's core aim is to provide access to nine of the complementary world-class large-scale facilities: GANIL (F), GSI (D), joint LNL-LNS (I), JYFL (FI), KVI-CART (NL), CERN-ISOLDE (CH), ALTO (F), joint IFIN-HH/ELI-NP (RO) and NLC (PL). These facilities provide stable and radioactive ion beams of excellent qualities ranging in energies from tens of keV/u to a few GeV/u and intense photon beams up to 20 MeV energy. The stable-ion beams range from protons to uranium. Radioactive-ion beams are produced using the two complementary methods of in-flight fragmentation (IFF) and isotope separation on-line (ISOL), so that several hundred isotopes are available for the users. At ELI-NP, the high-intensity, high-energy photon beams are produced by laser back-scattering from high-energy electron beams. It is worth noting that IA support will be offered for the first time for the joint IFIN-HH/ELI-NP infrastructure in Romania and the NLC infrastructure in Poland. This is in fulfilment of the plan made in the IA ENSAR under FP7 and in accordance with the spirit of enlarging the ERA (European Research Area). In addition to nuclear structure and nuclear astrophysics research at these facilities, multidisciplinary and application-oriented research will be pursued. Furthermore, the infrastructure ECT* (I) will provide a unique place for meetings, seminars and workshops. ENSAR2 proposes open access to the above-mentioned ten top-level European infrastructures. These infrastructures will be offering access to a very large, wide and diverse user community from the EU and associated countries and for the first time to international users. The facilities will also provide an increased amount of beam time for applications of nuclear techniques.

Joint Research Activities

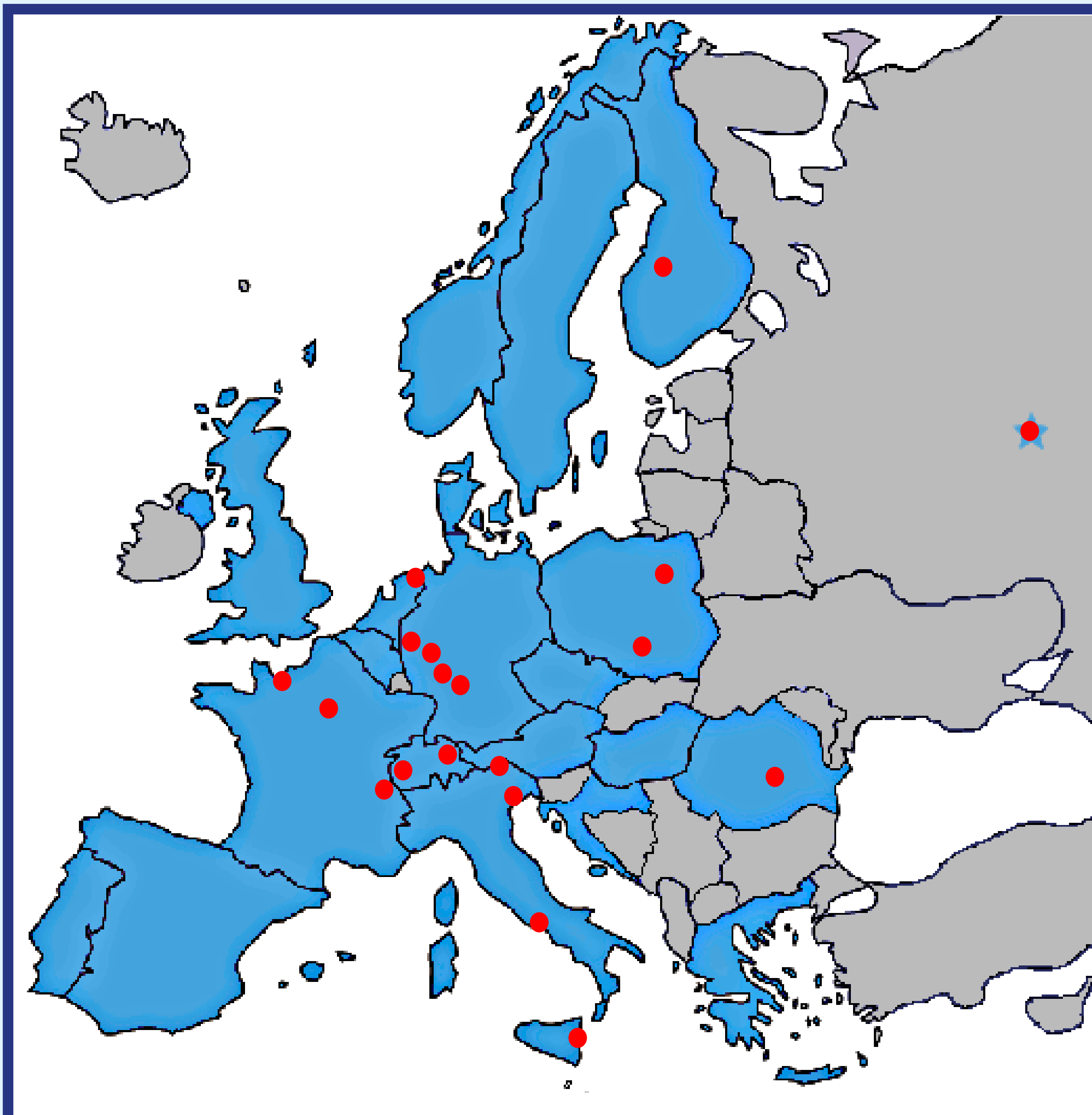
To enhance the access to these facilities, the community has defined a number of JRAs using scientific and technical promise as the main criteria. These activities deal with novel and innovative technologies to improve the operation of the facilities and make the most efficient and effective use of these facilities. They are in general relevant to more than one facility. These activities involve all facets of operation of an accelerator facility starting with the improvement of laser techniques for the production and study of radioactive-ion beams and various developments for ISOL beam production and use. In parallel, technological developments on accelerators, spectrometers and electronics will be performed for stable-ion beam facilities with the direct applications of the production of radioisotopes for medicine and the improvement of technologies and methods for the simultaneous detection of particles and gamma rays with same type of detectors and 3-dimensional gamma-ray tracking with high-resolution germanium detectors. In addition, general platforms for physics models, and analysis tools will be created and a study on data management will be performed. The development of modern theoretical tools for describing, interpreting, and predicting experimental results will support the work in nuclear-physics facilities. Particular importance is attributed to all RTD work, which will or might lead to industrial applications, as radioisotopes, scintillators, 3-dimensional position-sensitive detectors or new concepts for solid-state laser technology. This implies also applying state-of-the-art developments to other fields and to benefit humanity (e.g., archaeology, medical imaging).

Networking Activities

The NAs of ENSAR2 have been set-up with specific actions to strengthen the community's work in TAs and JRAs. They promote foresight studies for new instrumentation and methods, stimulate complementarity, ensure a broad dissemination of results and stimulate multidisciplinary and application-oriented research and innovation at the RIs. They aim to strengthen the communities' coherence regarding particular research topics, to pool resources and to provide instruction courses to users. In this vein, the scientific interests of the nuclear structure and nuclear astrophysics communities are discussed to optimise use of the large RIs.

Specifically, cooperation about ECR ion sources completes beam developments in JRAs. Dissemination on nuclear spectroscopy instrumentation and gas-filled detectors and systems ensures an efficient transfer of knowledge between scientists. Enhancement of collaboration between large-scale and small-scale facilities improves the development and tests of high-level equipment and enhances training of young researchers. Networks stimulate also relationships with industry and application-oriented research, in particular about technologies for nuclear medicine and studies of radiation biological effects. In addition, the managing network will insure a smooth running of the integrating activity as a whole in all aspects of technical, scientific, financial, administrative, contractual and legal activities. It will supervise an impact study on TA infrastructures and on ENSAR2 itself, and will also stimulate dissemination of knowledge and outreach activities.

RESEARCH INFRASTRUCTURE AND NETWORKING



From North to South:
JYFL (Jyväskylä, Finland), **JINR** (Dubna,Russia),
KVI-CART (Groningen, The Netherlands), **HIL** (Warsaw, Poland),
GANIL (Caen, France), **COSY** (Jülich, Germany), **ELSA** (Bonn, Germany),
MAMI (Mainz, Germany), **GSI** (Darmstadt, Germany), **ALTO** (Orsay, France),
CCB (IFJ, PAN Kraków, Poland), **ILL** (Grenoble,France),
CERN (Genève, Switzerland), **PSI** (Villingen, Switzerland),
ECT* (Trento, Italy), **LNL-INFN** (Legnaro, Italy), **IFIN-HH** (Bucharest, Romania),
LNF-INFN (Frascati, Italy), **LNS-INFN** (Catania, Italy)

RESEARCH INFRASTRUCTURE AND NETWORKING

EXISTING RESEARCH INFRASTRUCTURES AND UPGRADES

Theory and Computing

*ECT**, Trento, Italy

The European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) started operating in 1993 as a 'bottom up' initiative of the European nuclear physics community and has since developed into a very successful research centre for nuclear physics in a broad sense. ECT* is unique and the only centre of its kind in Europe. It is similar in scope and mission to the Institute for Nuclear Theory in Seattle (INT), USA, and collaborates with European Universities, Institutes and laboratories. It is an institutional member of NuPECC, the Associated Nuclear Physics Expert Committee of the European Science Foundation. With around 700 scientific visitors each year, from all over the world, spending from a week to several months at the Centre, ECT* has gained a high visibility. As stipulated in its Statutes, ECT* assumes a coordinating function in the European and international scientific community by:

- conducting in-depth research on topical problems at the forefront of contemporary developments in theoretical nuclear physics
- fostering interdisciplinary contacts between nuclear physics and neighbouring fields such as particle physics, astrophysics, condensed matter physics, statistical and computational physics and the quantum physics of small systems
- encouraging talented young physicists by arranging for them to participate in the activities of the ECT*, by organizing training programmes and establishing networks of active young researchers
- strengthening the interaction between theoretical and experimental physicists

These goals are reached through international workshops and collaboration meetings, advanced doctoral training programmes and schools, and research carried out by postdoctoral fellows and senior research associates as well as long term visitors. Cooperations exist with the Physics Department and the Center for Bose-Einstein Condensation (BEC) at the University of Trento and with the Interdisciplinary Laboratory for Computational Science (LISC) of the Bruno Kessler Foundation. There are presently cooperative agreements with other scientific institutions, in particular the ICTP in Trieste, the Extreme Matter Institute (EMMI) in Darmstadt, the Helmholtz International Center for FAIR, the JINR in Dubna, the research Center RIKEN, the National Astronomical Observatory of Japan, the ITP of the Chinese Academy of Science and the Asia Pacific Center for Theoretical Physics in Korea.

ECT* is sponsored by the "Fondazione Bruno Kessler" in cooperation with the "Assessorato alla Cultura", (Provincia Autonoma di Trento) and funding agencies of EU Member and Associated States. It also receives support from various instruments of the Framework Programmes of the European Commission.

With the emergence of a common European Research Area (ERA) and growing international cooperation ECT* faces new opportunities and challenges. Significant European and global investments are made presently in accelerator centres and other experimental facilities. Their efficient utilisation requires coordination and exchanges of ideas – experiments stimulating theory and vice versa. Interdisciplinary contacts between the various subfields covered by ECT* and with related areas of physics and science is beneficial to all parties.

European Computing Infrastructure

Most of the advances in modern nuclear theory have become and continue to be possible through major investments in the European computing infrastructure. This infrastructure is provided at the national level and the resources are coordinated through the "Partnership for Advanced Computing in Europe" (PRACE) for the scientific community.

National HPC resources

France

The main organization for high-performance computing (HPC) in academic areas in France is GENCI (Grand Equipment National de Calcul Intensif). The French national computing resources, made available by GENCI for the scientific communities, are installed and operated in three computing centers: the Très Grand Centre de calcul du CEA (TGCC) at Bruyères-le-Châtel near Paris, the Institut du développement et des ressources en informatique scientifique (Idris) of CNRS at Orsay and the Centre informatique national de l'enseignement supérieur

(Cines) at Montpellier. In particular TGCC is an HPC infrastructure, hosting Petascale supercomputers. This supercomputing centre has been planned to host the first French Tier-0 machine Curie with a peak performance of 1.75 Pflop/s.

Germany

In Germany, the "Gauss Centre for Supercomputing" (GCS) is the leading Tier-0 centre in Europe. GCS is the alliance of the three national supercomputing centres, the High Performance Computing Centre Stuttgart (HLRS), the Jülich Supercomputing Centre (JSC), and Leibniz Supercomputing Centre, Garching near Munich (LRZ). A CRAY XC40 system is installed at the HLRS with a peak performance of 7.42 Pflop/s. JSC provides access to the IBM Blue Gene/Q system JUQUEEN with a peak performance of 5.9 Pflop/s. In addition, the JSC hosts the general-purpose cluster JURECA with a peak performance of more than 2.2 Pflop/s. The third GCS HPC system SuperMUC is located at the LRZ in Garching, delivering a peak performance of 6.8 Pflop/s. A successor for JUQUEEN with a target peak performance of about 50 Pflop/s will be installed at JSC in several stages, starting in 2018.

Italy

The main organization for high performance computing in academic areas in Italy is CINECA, which is a non-profit Consortium of 70 Italian universities and 5 institutions and features the system Marconi. The Marconi system has two different partitions: Marconi-A1 with a peak performance of 2 Pflop/s and Marconi-A2, which is based on a multi-core architecture and the peak performance will be boosted to approximately 13 Pflop/s. In the middle of 2017 the first partition will be replaced by a new one reaching a total computational power in excess of 20 Pflop/s. The second CINECA system is the Tier-1 IBM cluster system Galileo, which went into operation in 2016 and provides a peak performance of about 1Pflop/s.

The IBM Blue Gene/Q system JUQUEEN with 5.9 Pflops peak performance at the computing center of the Forschungszentrum Jülich

Spain

Academic high-performance computing in Spain is organised through the network RES ("Red Española de Supercomputación"). RES is an alliance of 12 academic institutions and their supercomputers and is coordinated by the Barcelona Supercomputing Centre (BSC). One of these machines, MareNostrum, located at BSC is a multi-core installation and currently consists of roughly 50,000 cores. This amounts to a peak speed of around 1Pflop/s.

Switzerland

The Piz Daint supercomputer is the flagship HPC system of the "Swiss National Supercomputing Centre" (CSCS) in Lugano. Having been installed in 2016, it is a Cray XC50 system with a total of 206,720 computing cores amounting to a peak performance of nearly 16 Pflop/s. It currently ranks number 8 in the Top500 list.

United Kingdom

In the UK computational nuclear theory is part of DiRAC (Distributed Research utilising Advanced Computing), the integrated supercomputing facility for theoretical modelling and HPC-based research in particle physics, nuclear physics, astronomy and cosmology. Academic users have access to a total of five installations, including clusters (Cambridge, Durham, Leicester) and a BlueGene/Q facility (Edinburgh), with a combined performance of 2 Pflop/s. DiRAC is funded via the national Science and Technology Facilities Council (STFC), which covers nuclear physics besides particle physics and astronomy. A succession to the current facilities is being planned and expected to arrive during 2017.

In addition to the major Tier-0 facilities there are a number of national supercomputing resources. In Ireland, there is the national centre for high-performance computing – ICHEC. Via the supercomputer Fionn it provides access through peer-reviewed applications for nuclear theory. There are other installations largely dedicated to nuclear theory, as for instance QPACE2 in Regensburg, QPACE3 at the Jülich Supercomputing Centre, MOGON in Mainz, WALES in Wales and the LOEWE CSC in Frankfurt.

High-performance Computing at the European level

At the European level the use of national compute infrastructures is coordinated through PRACE. PRACE has currently 25 member countries and offers high-performance computing and data management resources through access to national Tier-0 HPC facilities in a peer review process. The computer systems and their operations are provided by five PRACE members (BSC in Spain, CINECA in Italy, SNCS in Switzerland, GCS in Germany and GENCI in France) with a total of about 46 Pflop/s. Over the entire period of its operation PRACE has distributed about 15% of the resources to basic science, out of which 21% have gone into the research field "Fundamental Constituents of Matter". In addition, PRACE manages DECI - the Distributed European Supercomputer Initiative, which provides European Tier-1 access to architectures made available by various European countries.

Concerning the future of HPC at the European level, PRACE is heavily involved in the strategy for European Exascale computing. Planning of future HPC installations is recognized as being of strategic importance for all international players. Roadmaps towards Exascale computing facilities and planning for next generation installations are underway in Europe as well as in the USA and Asia. All major computing centres organized in PRACE aim for new installations in the next years that will reach a peak performance in the 10-30 Pflop/s range.

Lepton Beam Facilities

COMPASS, CERN, Switzerland

COMPASS is a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN. The Collaboration consists of nearly 240 collaborators from 13 countries and 28 institutes. The purpose of the experiment is the study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams.

The spectrometer was installed in 1999 - 2000 and was commissioned during a technical run in 2001. In 2010 and 2011 structure function measurements with a polarised proton target continued. In 2009/2012 dedicated measurements for the pion polarizability were performed.

In 2010 the COMPASS-II proposal was approved envisaging a physics programme for the years 2012-2018 comprising in particular

- tests of chiral perturbation theory (2012),
- measurements of transverse-momentum-dependent parton distributions in polarised Drell-Yan (DY) reactions (2015/18)
- measurements of generalised parton distributions (GPD) in exclusive processes, in particular in deeply virtual Compton scattering with a liquid hydrogen target. Semi-inclusive DIS will be measured in parallel (2016/17).

Plans for a programme beyond 2020 are being developed and will include GPD measurements with a polarised target and - in the longer term - DY and spectroscopy experiments with RF-separated kaon and antiproton beams. A proposal is planned to be submitted in 2017.

ELSA, Bonn, Germany

The Electron Stretcher Accelerator (ELSA) *(http://www-elsa.physik.uni-bonn.de/)* is a facility run by the University of Bonn / Physikalisches Institut and thus under the auspices of the German federal state Nordrhein-Westfalen. It consists of two electron LINACs, a booster synchrotron and an electron stretcher ring. Unpolarised or polarised electron beams are injected into the synchrotron by LINACs I or II, at energies around 20 MeV. They are then accelerated to typically 1.2 GeV and transferred into the stretcher ring. The latter can be operated in booster, stretcher, and storage mode. In the booster mode, normally used for hadron physics experiments, several pulses from the synchrotron are accumulated (internal current typically 20 mA). The electrons are further accelerated to a maximum of 3.5 GeV, slowly spilled via resonance extraction and delivered to experiments with a typical spill time of 4 – 6 sec. Furthermore, a new beamline connected to the stretcher ring is currently being commissioned. It will provide electron beams to an area for detector tests and characterisation up to the full energy with currents of 1 fA – 100 pA and a duty-factor of approx. 80 %.

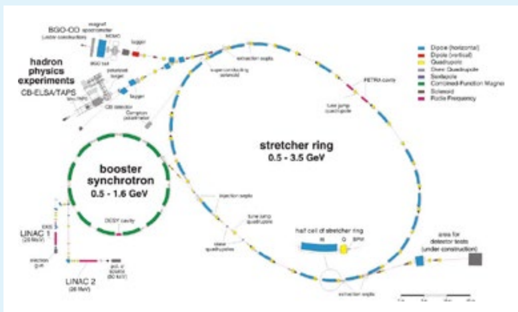
The research focus at ELSA is on hadron physics. Furthermore, ELSA is used as a test facility for detector physics.

The hadron physics programme is devoted to baryon spectroscopy via meson photo-production. After the termination of the Transregional Collaborative Research Center SFB/TR 16 *(http://sfb-tr16.physik.uni-bonn.de/)* in June 2016, ELSA will continue to provide beam for the existing hadron physics experiments to allow for the best exploitation of their physics potential.

Two experimental areas exist, each equipped with photon tagging systems including diamond radiators to provide linearly polarised photon beams:

• CBELSA/TAPS

(http://wwwnew.hiskp.uni-bonn.de/cb/)



Schematic layout of the facility ELSA, Bonn, Germany

The CBELSA/TAPS experiment which combines the Crystal Barrel and the TAPS electromagnetic calorimeters is ideally suited to investigate the photoproduction of neutral mesons decaying into photons with a nearly complete solid angle coverage. Together with the polarised frozen spin target and a circularly or linearly polarised photon beam, single and double polarisation experiments have been successfully performed in the past and are planned for future.

• BGO-OD

(http://b1.physik.uni-bonn.de/)

BGO-OD is a newly commissioned experiment based on a BGO ball central calorimeter, previously used in the GRAAL experiment at Grenoble, and a large aperture forward magnetic spectrometer. It allows detection of complex final states of neutral and charged particles, including forward going fast hadrons. This is complementary to the CBELSA/TAPS setup and other similar experiments.

• Detector tests

Detector tests are pursued in two areas. At LINAC I, a pulsed high current 20 MeV beam can be used for material irradiation. The new beamline will provide beam for detector development. Both test areas serve as a facility for the Centre for Detector Physics FTD currently under construction on the University of Bonn campus.

Both the test beam facility and the hadron physics experiments are open to external proposals for collaboration.

INFN-LNF, Frascati, Italy

The Frascati National Laboratories (LNF) [http://www.lnf.infn.it], founded in 1955, are the oldest and largest laboratory of the National Institute of Nuclear Physics (INFN) in Italy. They were built to host the Electron Synchrotron (1.1 GeV), a world record at that time. The first prototype of an electron-positron storage ring ADA was then built, and after that, the large electron-positron collider ADONE (3 GeV in centre of mass) led to discovery of the color structure of the quarks. At ADONE, the very active community pushed innovative techniques still in use worldwide: monochromatic beams of bremsstrahlung photons and the first Compton backscatter beam.

The e^+e^- meson factory DAΦNE, 1020 MeV c.m. energy, has been operated for more than 15 years. A broad physics programme ranging from the study of CP and T violation in kaon decays and of hadron physics to that of hypernuclei and kaonic atoms has been pursued. The DAΦNE machine, with the KLOE2 experiment operating at the interaction point has reached luminosities of 2.2 x 10^{32} cm^{-2} s^{-1} , two orders of magnitude larger than those of previous generation colliders. One of the key-points for the luminosity increase has been the use of the Crab Waist (CW) collision scheme, currently under test also at Super-KEKB facility.

This long programme of activity at DAΦNE, performed by the KLOE (KLOE2), DEAR, FINUDA and SIDDHARTA experiments, led to unprecedented results in some of the main fields of CP, CPT, hadron and strangeness physics.

Currently the machine is running with the upgraded KLOE2 detector, with the goal of collecting 5/fb by the end of 2017. The KLOE2 detector has a better hermetic coverage and an improved vertexing capability, which should allow more precise measurements of quantum interferometry and of K_{short} decays. In 2018 the upgraded SIDDHARTA2 detector will be installed, to study kaonic deuterium X-ray transitions, as being one of the most important measurements in the strangeness sector of low-energy QCD.

At the same time LNF pursues goals in different fields of research: elementary and astro-particle physics, theoretical physics, multidisciplinary activities with synchrotron radiation beams, and detector and accelerator developments with the Beam Test Facility of the DAΦNE LINAC.

A new laboratory (SPARC_LAB) has been set up, with a high brightness electron beam driving the Self Amplified Spontaneous Emission-Free Electron Laser (SASE-FEL) in the green light.

The SPARC injector, in conjunction with the very powerful infrared laser FLAME (light pulse of 300TW and 25 fs width), will allow investigations into the physics of plasma wave-based acceleration and the production of X-rays via Compton scattering.

The SPARC_LAB Laboratory is fully involved in the EUPRAXIA design study, funded in H2020, to prepare a proposal for an European facility for plasma accelerated 5 GeV electron beam, to drive an FEL infrastructure.

Picture of the e^+e^- meson factory DAΦNE INFN-LNF, Frascati, Italy

MAMI, Mainz, Germany

The MAMI (Mainz Microtron) electron accelerator is operated by the Institute of Nuclear Physics of the Johannes Gutenberg University of Mainz, which receives a dedicated support by the state of Rhineland-Palatinate for the maintenance and the operation of the accelerator. The Institute is also running the DFG-funded Collaborative Research Centre CRC 1044 (*The Low-Energy Frontier of the Standard Model*) and is involved in the Cluster of Excellence PRISMA (*Precision Physics, Fundamental Interactions, and Structure of Matter*).

The MAMI continuous wave (CW) accelerator consists of sources for unpolarised and polarised electrons, followed by an injection linac, three consecutive race-track-microtrons and a harmonic double-sided microtron (HDSM) providing a maximum beam energy of 1.604 GeV. Hallmarks of the MAMI accelerator are the excellent beam intensity of up to 100 μA, a high degree of beam polarisation of up to 85%, and an energy resolution of 10^{-4}. With these beam parameters, MAMI and its experiments are ideally positioned for highly competitive investigations in the field of hadron physics.

Currently, two major experimental setups are operated at MAMI: the A1 high-resolution spectrometer setup, and the A2 experiment at the tagged photon beam line, which consists of the large acceptance Crystal Ball detector together with the TAPS calorimeter wall.

The A1 collaboration operates a setup of five magnetic spectrometers. The core components are three big spectrometers of 300 tons each with momentum resolutions of 10^{-4}. The focal planes of these spectrometers comprise drift chambers, scintillators as well as timing detectors, Cherenkov detectors, and a proton polarimeter. The collaboration also provides a short orbit spectrometer for momenta of up to 200 MeV/c, especially suited for threshold-electro production of pions, and a compact spectrometer (KAOS) for kaons with momenta of up to 1900 MeV/c. A highly segmented large solid angle neutron detector is under construction. High-power cryo-targets for liquid hydrogen and deuterium, pressurised ^{3}He and ^{4}He and polarised ^{3}He targets are available as well.

The A2 collaboration runs a facility for energy tagging of bremsstrahlung photons designed by physicists from the Glasgow and Edinburgh Universities. An additional end point tagger was built to cover the high-energy part of the photon energy spectrum and to access the η' threshold. The primary detector arrangement consists of the Crystal Ball and TAPS detectors. This setup is particularly suitable for the detection of photons with a solid angle of almost 4π with high resolution and count rate capability. A polarised frozen-spin target for protons and deuterons with longitudinal and transverse polarisation is operating successfully. Additional targets and sub-detectors are available.

At MAMI, the most precise measurement of the electric proton radius in an electron scattering experiment has been achieved benefiting from the high resolution of the A1 magnetic spectrometers. Form Factors of mesons are measured with the A2 setup by analyzing Dalitz decays of pseudoscalar as well as vector mesons. The production rates for η, η', and ω mesons in the clean background environment of MAMI are among the highest in the world.

Polarisabilities of the proton, neutron and pion can be approached by the A1 as well as the A2 Collaborations. For the near future also Compton scattering experiments of light nuclei are foreseen. The polarised frozen-spin target at the tagged photon facility A2 allows for a significant progress in real Compton scattering experiments by using single or double polarisation observables.

To obtain a deeper understanding of the dynamical origin of baryon resonances beyond the naive quark model a set of well-selected states in reach at MAMI-C beam energies are currently investigated. This implies on the experimental side precision measurements of transition form factors in electro production (A1 collaboration), measurements of radiative decays and the full exploitation of polarisation degrees of freedom using the polarised target (A2 collaboration) in conjunction with the polarised MAMI beam.

More recently, searches for GeV-scale vector particles of a hypothetical dark sector, also known as Dark Photons, have been carried out very successfully at A1/MAMI. These searches are highly motivated by a number of astrophysical anomalies as well as precision observables of the Standard Model and lead to a world-wide hunt for Dark Photons. The Mainz results lead to the most stringent limits for the existence of Dark Photons in an important parameter range.

Precision measurements of the kaon - nucleon interaction and of light hypernuclei are of utmost importance to validate the various theoretical approaches presently trying to bridge this gap between nuclear and hadron physics. At MAMI the forward spectrometer KAOS is of central importance for these investigations.

Ab initio Lattice QCD calculations can be performed thanks to the availability of several dedicated High Performance Computing (HPC) clusters at Mainz.

Hadron Beam Facilities

ALICE, CERN, Switzerland

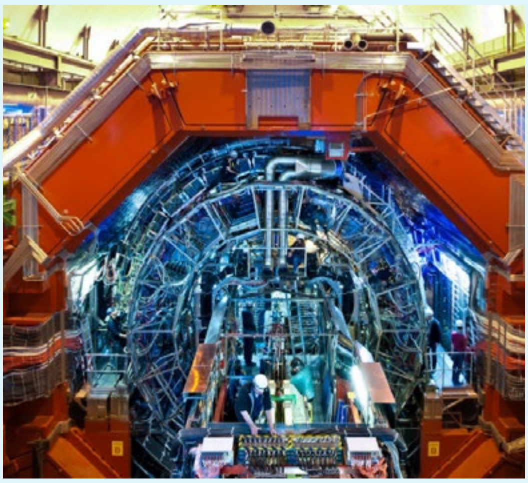
The ALICE Collaboration (42 countries, 169 institutes and over 1600 collaborators) has built a dedicated heavy-ion detector to exploit the unique physics potential of nucleus - nucleus interactions at the Large Hadron Collider (LHC) energies.

The aim is to study the physics of strongly interacting matter at extreme energy densities, where the formation of a new phase of matter, the quark-gluon plasma, is expected. The existence of such a phase and its properties are key issues in QCD for the understanding of quark confinement and of chiral-symmetry restoration. For this purpose, a comprehensive study of the hadrons, electrons, muons and photons produced in the collision of heavy nuclei is required utilising lead beams at various energies. ALICE is also studying proton-proton and proton-lead collisions both as a comparison with lead-lead collisions and in physics areas where ALICE is competitive with other LHC experiments.

During the Run1 of LHC ALICE has taken data studying proton-proton collisions and, in 2010 and 2011, lead-lead collisions at 2.76 TeV per nucleon, and in 2013 proton-lead collisions at 5.02 TeV per nucleon.

During first long shutdown (2013 and 2014) ALICE has been considerably upgraded with the installation of a second arm of Electromagnetic Calorimetry (DCAL), of a fourth module of Photon detector, the completion of the TRD and forward shower counters (ADA).

Data taking in Run2 (2015 to 2018) is now in progress, at a proton-proton energy of 13 TeV and lead-lead of 5.02 TeV. A proton-lead run is planned for late 2016. ALICE is expected to collect in Run2 about 10 times the statistics of Run1. A major Upgrade for ALICE is foreseen for the Long shutdown 2 (2019-2020) and is described in the future facilities section.



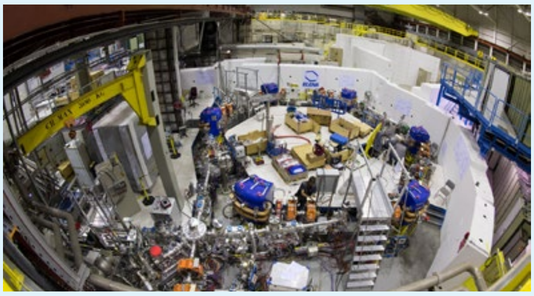
Picture of the ALICE detector at LHC CERN, Switzerland

ALICE has so far produced an impressive harvest of scientific results. They include a thorough study of the global features of the collisions, the measurement through the study of flow patterns of the viscosity to entropy ratio of the plasma, extremely low even at the high temperatures, the energy loss of partons in QGP, including heavy quarks, and the first evidence for regeneration of charmonium in the plasma. In addition, remarkable and unexpected features of proton-nucleus collisions have been observed, which are compatible with collective behaviour even in such small systems. Finally, a wealth of new measurements on the structure of hadrons and nuclei at low-x and on soft QCD have been produced.

Antiproton Decelerator (AD), CERN, Switzerland

The Antiproton Decelerator (AD) at CERN was commissioned in 2000 and has been providing low-energy (100 MeV/c) antiprotons to a number of experiments since then. The goal of these experiments has been the study (and the development of the techniques to produce, trap, cool or form atomic beams) of cold antihydrogen atoms (for tests of CPT and of the weak equivalence principle), as well precision measurements of antiprotons or precision spectroscopy of antiprotonic helium in view of determining with high precision the parameters of antiprotons and fundamental constants, and to study the effects of antiprotons on biological ensembles.

Starting from 2006 the ATRAP and ALPHA experiments have succeeded in trapping small numbers of antihydrogen atoms, and are taking the next steps on a long road of increasingly precise laser and microwave spectroscopy of these trapped atoms, through improved antiproton capture rates, the production of cold electron and positron plasmas, low temperature preparation and mixing of positron and antiproton plasmas, including the successful demonstration of evaporative cooling for antiprotons, and attempts towards laser-cooling of trapped antihydrogen. The goal of cooling the trapped antihydrogen atoms, and carrying out first laser spectroscopic measurements remains an endeavour that requires painstaking efforts, both technical as well as experimental, and that is constrained by the limited number of available antiprotons. Antihydrogen will constrain possible violations of both CPT and the WEP.



Picture of the ELENA ring at the AD facility at CERN in Switzerland

ASACUSA continues to perfect their spectroscopic measurements on antiprotonic helium. The sensitivity of this method has allowed ASACUSA to reach an impressive level of precision in the determination of fundamental constants, such as the electron to antiproton mass ratio and the antiproton magnetic moment, although the latter are no longer competitive with very recent direct measurements by ATRAP or BASE. In addition, ASACUSA is also laying the groundwork towards producing a beam of antihydrogen, in view of measuring the hyperfine splitting of ground-state antihydrogen to the high level that the same group has already achieved with a beam of atomic hydrogen. Another experiment, AEGIS, is developing the technologies needed to measure, with a pulsed beam of cold antihydrogen atoms, the gravitational coupling between matter and antimatter; such a beam would also allow an improved hyperfine splitting measurement. Finally, BASE has, since 2014, focused on highly precise measurements of the antiproton's magnetic moment and its charge-to-mass ratio in a dedicated Penning trap.

These experiments, as well as a newly approved experiment, GBAR, which will also attempt to test the WEP with antihydrogen atoms, will either benefit from an increase in the number of very low energy antiprotons, currently limited by the need to degrade the energy of the antiprotons delivered from the AD (100 MeV/c) down to the keV range that allows trapping, or – in the case of GBAR – crucially rely on such increased numbers of slow antiprotons. The present approved programme of the AD extends into the mid-2020's; to meet this increasing need for antiprotons both by the approved experiments as well as to permit further experiments to take place, an addition to the AD, a further deceleration stage down to 100 keV called ELENA, has been approved in 2011. After five years of design and construction, it is presently undergoing commissioning and will be operational from 2017 onwards, providing fast-extracted beams of 100 keV antiprotons to up to four experiments in parallel, and foreseeing additional space for future initiatives.

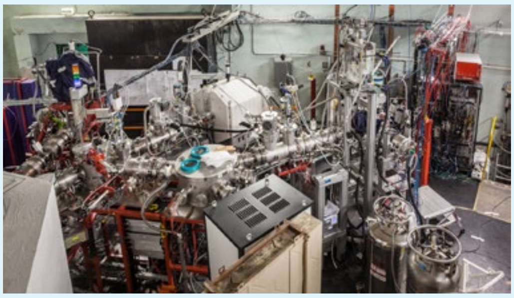
ALTO, Orsay, France

The ALTO facility has two accelerators providing radioactive-, stable- and cluster beams for nuclear structure, atomic physics, cluster physics, biology and nanotechnology studies. The *Tandem Accelerator* (operated up to 14.6 MV) delivers beams from protons to gold (including rare ions as ^{14}C, ^{48}Ca) and also "Cluster-beams" micro-droplets (C60 and gold droplets). The *ALTO electron linear accelerator* (50 MeV 10µA) is used as a driver to induce fission in a thick uranium carbide target (up to 10^{11} fissions/s). The fission products are extracted from the target using surface ionisation, plasma or resonant ionisation laser ion source (RIALTO) and mass separated before being sent to different experimental setups. These beams are of great interest for study in nuclear structure, decay heat in reactors and solid-state physics. Research and development on target and ion sources for the next generation radioactive ion beam facilities (SPIRAL2, EURISOL ...) are among the key activities at ALTO.

The laboratory has a rich palette of research instrumentation and several services (HPGe Detector, target, laser, laboratories and experimental hall services).

Research instrumentation

- PARRNe is an ISOL mass separator (M/ΔM ~1500) that provides low-energy (30 keV) radioactive beams. Fully operational is the BEDO setup, offering the possibilities for beta-decay studies, while the POLAREX set up (for low-temperature nuclear orientation and nuclear moment studies) is being prepared.
- SIHL is an off line separator dedicated for the test and the R&D on target ion sources used at PARRNe.
- Split Pole is a magnetic spectrometer used to measure "two body" reactions with a very high resolution.
- *ORGAM* is a Ge multidetector array for gamma-spectroscopy (nuclear structure) which can be associated with a number of ancillary devices. Several experimental campaigns (MINORCA, PARIS, nu-ball) are being organised on a regular base.
- LICORNE is a kinematically focused, fast neutron source (with neutron energy from 0.5 to 7 MeV) using ^{7}Li or ^{11}B projectiles. The presently available fluxes (~10^7 n/s/sr) are employed for fundamental and applied physics studies.
- AGAT is a new generation of detection apparatus used in Cluster Physics for atomic astrophysical studies.



Picture of beamlines and instrumentation at the ALTO facility Orsay, France

There are currently four projects planned for the future to enlarge considerably the variety of techniques applicable at ALTO and the physics cases that could be addressed.

- *nu-ball* hybrid array, a hybrid $LaBr_3$-Ge array for gamma spectroscopy (including lifetimes) in nuclear structure studies. This instrument will combine 24 clover detectors from the European Gamma pool and 30 $LaBr_3$ detectors from the FATIMA collaboration.
- LINO – laser-induced nuclear orientation setup for nuclear moment, charge radii and polarised beta-decay studies (beta-NMR and/or NQR also with polarised beams).
- MLL-trap – Penning-trap setup for high-precision mass measurements as well as trap-assisted spectroscopy. This set up is already constructed and tested at the Maier-Leibnitz Laboratory (MLL), Germany and to allow its use at ALTO a radio-frequency quadrupole Paul trap (RFQ) will be constructed in Orsay (first tests by 2019).
- The move and installation of the Split Pole spectrometer in a different experimental area, that would allow for its efficient use independently from the radioactive ion beams setups.

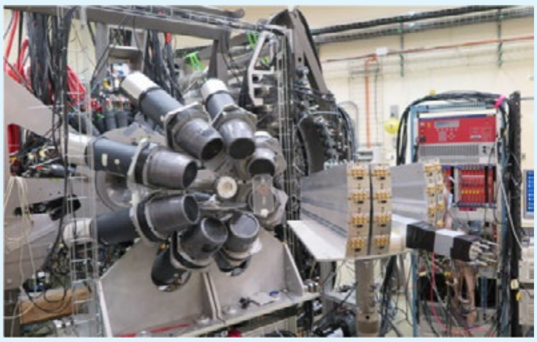
CCB, IFJ PAN, Kraków, Poland

The Cyclotron Centre Bronowice (CCB) is a research infrastructure located on the premises of the Institute of Nuclear Physics of the Polish Academy of Sciences, serving research in the area of nuclear and medical physics, being also a centre of proton radiotherapy, unique in Central Europe. It operates two cyclotrons: the K=60 MeV light-ion cyclotron AIC-144 and the new Proteus-235 cyclotron which delivers a proton beam in the energy range of 70-230 MeV. A very important characteristic of the Proteus-235 cyclotron is that the beam energy can be changed within tens of seconds.

The research programme in the field of nuclear physics at the CCB encompasses: i) measurements of collective, high-energy excitations in nuclei (e.g., pygmy and giant nuclear resonances) in the yet unexplored regions of excitation energy and spin, ii) gamma decay from unbound states in light nuclei, iii) direct and statistical decay of the deep-hole states populated by means of the (p,2p) reactions, iv) dynamics of a few-nucleon systems and physics of nuclear clusters aimed at getting a new insight into the nucleon-nucleon interaction (important in the light of theoretical efforts in developing links between nuclear physics and quantum chromodynamics), v) tests of elements of the modern detection systems that are being constructed for the large scale nuclear physics facilities in Europe (SPIRAL2, FAIR).

The main instrumentation at the CCB includes:

- High-energy gamma-ray detection system consisting of an array of eight large-volume BaF2 detectors (HECTOR array), which can be complemented with a few clusters of the PARIS array and large volume $LaBr_3$ scintillators;
- Big Instrument for Nuclear Data Analysis (BINA) detection setup, which includes a liquid-target assembly, multi-wire chamber and scintillation hodoscope;
- Kraków Triple Telescope Array (KRATTA): a multi-modular array for charged-particle detection (which can be used in different configurations); it covers a broad energy range of protons that can be detected, from ~3 to 260 MeV, and provides mass resolution up to mass number A~10;
- a detector testing bench, offering possibility of testing the response functions in the wide proton energy range (70-230 MeV) of various detectors.



Picture of the main instrumentation at CCB IFJ PAN, Kraków, Poland: HECTOR (on the left) and KRATTA (on the right), and BINA (right, in the back).

Applied and interdisciplinary physics research is also an important activity at the CCB. It is carried out in the area of radiotherapy and radiobiology.

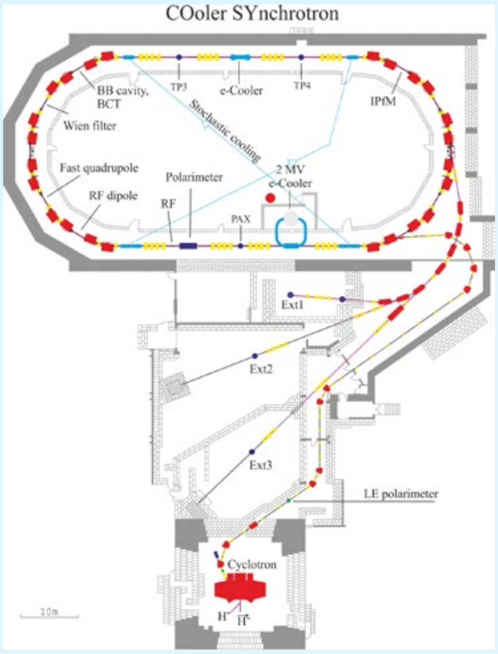
Research in the field of clinical medicine is another line of activity at the CCB. It aims at performing trials, which show the clinical efficacy of the state-of-the-art scanned proton beam technique in the treatment of selected tumours.

Because of the hadron therapy experiments have to be conducted during the time free of patients' treatment, i.e., mainly at nights and during the weekends.

COSY, Jülich, Germany

The COoler SYnchrotron (COSY) at the Institut für Kernphysik (IKP) of the Forschungszentrum Jülich (FZJ), Germany, is a worldwide unique facility which was utilised for hadron physics experiments until the end of 2014, and since then is used as a test and exploration facility for accelerator and detector development as well as for the preparation and execution of precision experiments to investigate symmetry violations in hadronic systems: a test of Time Reversal Invariance Violation (TRV) in double-polarised pd-scattering and a search for Charge-Parity Violation (CPV) via Electric Dipole Moments (EDM) of charged particles in storage rings.

The COSY facility comprises (i) sources for unpolarised and polarised protons and deuterons, (ii) the injector cyclotron JULIC, (iii) the synchrotron to accelerate, store and cool the beams, and



Schematic layout of the facility COSY, Jülich, Germany

(iv) internal and external target stations for experimental set ups.

H^- (D^-)-ions are pre-accelerated up to 0.3 (0.55) GeV/c in JULIC, injected into COSY via stripping injection and subsequently accelerated to the desired momentum below the maximum of 3.7 GeV/c. Three installations for phase space cooling can be used: (i) a low-energy electron cooler (for momenta between 0.3 and 0.6 GeV/c) installed in one of the straight sections, (ii) stochastic cooling above 1.5 GeV/c, and (iii) a high-energy electron cooler in the opposite straight section, which can be operated between 0.3 and 3.7 GeV/c. Well-established methods are used to preserve polarisation during acceleration. A fast tune jumping system, consisting of one pulsed air core quadrupole, has been developed to overcome intrinsic depolarising resonances. Preservation of polarisation across imperfection resonances is achieved by the excitation of the vertical orbit using correcting dipoles to induced total spin flips. The polarisation can be continuously monitored by an internal polarimeter (EDDA detector); a new polarimeter using the WASA forward detectors is being set up at TP3, and a new calorimeter-based (LYSO crystals) polarimeter is under development. For protons beam polarisation of 75% is achieved up to the highest momentum. Vector and tensor polarised deuterons are also routinely accelerated with a degree of polarisation up to 60%. Dedicated tools have been developed to manipulate the stored polarised beams; in particular a Siberian Snake has been delivered to COSY recently for the preparation of longitudinally polarised beams. It will be installed at TP4. Beams can also be extracted to three external target stations. After decommissioning of the internal ANKE- and WASA 4π-calorimeter as well as the external BIG KARL and TOF-spectrometer, these sites are now used for tests and commissioning of HESR, CBM and PANDA equipment for FAIR, e.g., beam cooling and diagnostics, detectors and targets.

Precision measurements on symmetries and their violations (TRV, CPV), pursued by the international TRIC- (Time Reversal Invariance at COSY) and JEDI- (Jülich Electric Dipole Moment Investigations) collaborations, now constitute the major new direction of research at COSY.

GANIL, Caen, France

GANIL (Grand Accélérateur National d'Ions Lourds) is a heavy ion accelerator complex delivering both, stable heavy-ion beams, ranging from ^{12}C up to ^{238}U in the energy range between a few keV to 95 MeV/nucleon, and radioactive beams produced either in flight, or with the ISOL method in the SPIRAL1 facility. GANIL is one of the foremost sites for exploring both the structure of exotic nuclei and dynamics of nuclear collisions under various conditions. In addition to Nuclear Physics, the facility has very strong programmes in atomic, condensed matter physics, and radio-biology. The facility consists of:

- two injector cyclotrons preceded by two ECR ion sources which can be operated in parallel, one of them being used for low energy experiments (about 1MeV/nucleon) in the IRRSUD experimental area, while the other one is used simultaneously as first acceleration stage for the high energy beam.
- CSS1 and CSS2: separated sector cyclotrons delivering respectively beams in experimental area labelled SME (medium energy exit) in the energy range 5-15 MeV/nucleon, and the full energy beams (E = 4-100 MeV/nucleon) to all experimental areas.
- SPIRAL: the CIME cyclotron accelerates stable and radioactive beams in the energy domain 2-25 MeV/nucleon.

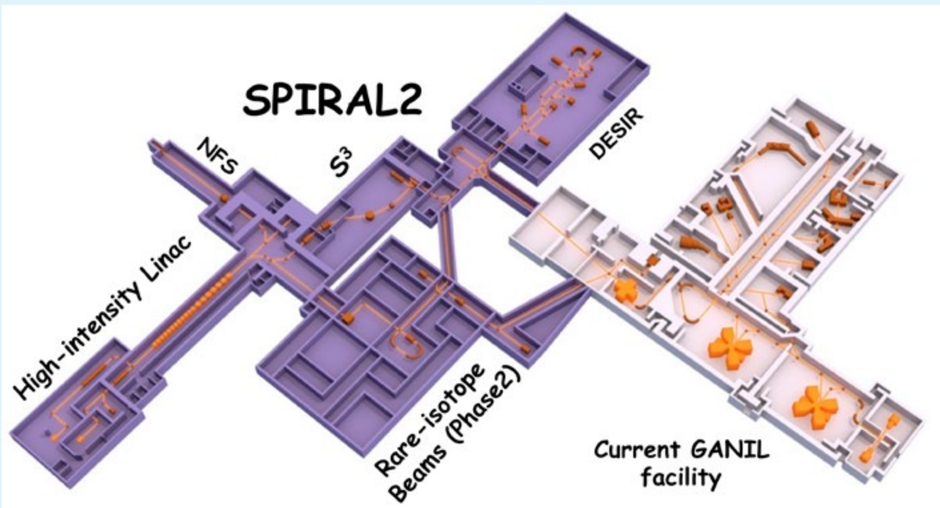
These secondary beams are produced by the ISOL method using the very intense primary GANIL beam impinging on a thick production target. An intense R&D programme on the target ion source systems is presently in progress, both for SPIRAL1 upgrade (to be commissioned in 2017) and the future SPIRAL2 facility (under commissioning).

The GANIL experimental halls are equipped with a very large range of versatile and state-of-the-art instrumentation. In particular, GANIL runs three large magnetic spectrometers:

- VAMOS is a large acceptance spectrometer and is used for various types of experiments: for the spectroscopy of single particle and collective states of exotic nuclei, using direct and deep inelastic reactions fusion-evaporation reactions and the use of Recoil Decay Tagging method to characterise heavy nuclei. It was built within a European collaboration (UK, Germany, France), and was also supported by a European RTD programme. The VAMOS detection system is today among the best performing ones in terms of heavy fragment mass and charge resolution.
- a high resolution spectrometer, SPEG, which has been intensively used for the study of discrete nuclear states, mass measurements of exotic nuclei, and the general study of nuclear excitations in peripheral collisions.
- the LISE III and LISE2000 spectrometers, mainly used today for experiments with radioactive beams produced "in-flight" on the production target located at the entrance of the spectrometer, which then isolates the projectile fragments from the flux of incident beam, focuses and unambiguously identify them. An additional velocity selection is obtained from a Wien filter. Finally the last magnetic dipole transforms the whole apparatus into a genuine mass spectrometer.

The variety of top level detectors at GANIL are used for investigations of exotic nuclei and nuclear reactions:

- the AGATA (campaign 2014-2020) & EXOGAM2 germanium arrays are large solid angle, high efficiency gamma-ray detectors, specially designed for stable-ion and RIB. Both devices were financed through large international collaborations.
- MUST2/TIARA and soon MUGAST: modular



Schematic layout of the facility GANIL, Caen, France

charged-particle detectors consisting of solid state detector telescopes dedicated to the study of direct reactions induced by radioactive beams on light targets. These are most often coupled with one of the spectrometers, and with EXOGAM.

- INDRA and soon FAZIA charged particle multi-detector systems for study of nuclear reactions and in particular of equation of state of nuclear matter.
- the PARIS and Chateau de crystal for high-energy gamma-rays for study of Giant Resonances in nuclei & nuclear structure;
- the MAYA and ACTAR-TPC active target-detectors for reactions with RIB,
- the NEDA and Neutron wall neutron detectors for in-beam γ-ray spectroscopy.

Moreover three beam lines are now available for Atomic and Condensed Matter Physics, at very low energy (below 1 MeV/nucleon, after the injector cyclotrons), at medium energy (after CSS1) and at full energy, allowing a broad range of experiments. A special beam line is also devoted to industrial beam applications, and to biological research. This activity has been considerably increased in the last few years, with the creation of a new laboratory dedicated to radiobiology inside the GANIL campus, and with special efforts to attract new industrial partners. The radiobiology activities are expected to grow at GANIL in the coming years, before the new hadrontherapy facility ARCHADE comes into operation. In total, between 50 and 60% of GANIL beam time (around 10000 hours) is allocated to interdisciplinary research and to applications, some with major potential implications for society: nuclear waste management, ageing of materials in nuclear power plants, radiobiology with heavy projectiles. Two types of industrial partners are particularly interested by the opportunities offered by GANIL heavy ion beams: the companies or agencies involved in the construction of electronic components for space applications (CNES, ESA, EADS, JAXA), and those building micro-porous films and membranes, or microstructures based on the development of this technology.

GANIL is thus a unique centre in Europe for studying interaction between ions and matter and is a host laboratory for a large community of around 700 users from more than 100 laboratories and 30 countries. The SPIRAL2 project presently under construction within a broad international collaboration will strengthen the European leadership in the field of exotic nuclei, and opens the road towards EURISOL, for which GANIL has been identified as a possible site.

The GANIL coordinates the EU HORIZON 2020 Integrating Activity contract ENSAR2 (European Nuclear Science and Applications Research 2) 2016-2020, putting together European nuclear physics community.

GSI, Darmstadt, Germany

The GSI Helmholtzzentrum für Schwerionen-forschung GmbH [http://www.gsi.de/] is operating a large accelerator complex, consisting of the linear accelerator UNILAC, the heavy-ion synchrotron SIS18 (with a magnetic bending power of 18 Tm), and the experimental storage-cooler ring ESR (with half the magnetic bending power of SIS18). With the UNILAC, heavy ions like U can be accelerated up to 12 AMeV, light ions (protons) up to 20 AMeV, in SIS18 ions are accelerated up to 2 AGeV and in ESR stable or radioactive ion beams can be stored and cooled at energies up to 0.56 AGeV (for U). Additionally, secondary pion beams can be delivered at momenta from 0.5 to 2.5 GeV/c.

The accelerators are complemented by about 20 experimental areas, equipped with modern spectrometers and detector systems, which offer outstanding possibilities for research in the fields of hadron and nuclear physics, atomic physics, plasma physics, materials science, biophysics and radiation medicine. The laboratory offers unique research possibilities to scientists from both domestic and foreign universities and other research institutions.

Equipment dedicated to hadron and (dense) nuclear matter research:

- High-Acceptance Di-Electron Spectrometer HADES to study the properties of vector mesons in nuclear matter with an high granularity time-of-flight detector with excellent time resolution (σ of 60-70 ps), and new DAQ system allowing up to 50 kHz event rate;
- Secondary beam facility for pion beams in the 0.5 to 2.5 GeV/c momentum range. Besides complementary experiments in the nuclear matter programme this opens up unprecedented possibilities in the field of medium-energy hadron physics;
- Detector test facility offering mixed electron, proton and pion beams to be used by e.g. the CBM and PANDA collaborations at FAIR.
- New opportunities for hadron and (dense) nuclear matter research in the next 5 years
- Replacement of the HADES pre-shower detector by an electromagnetic calorimeter for photon measurement to reconstruct π^0 and η mesons.

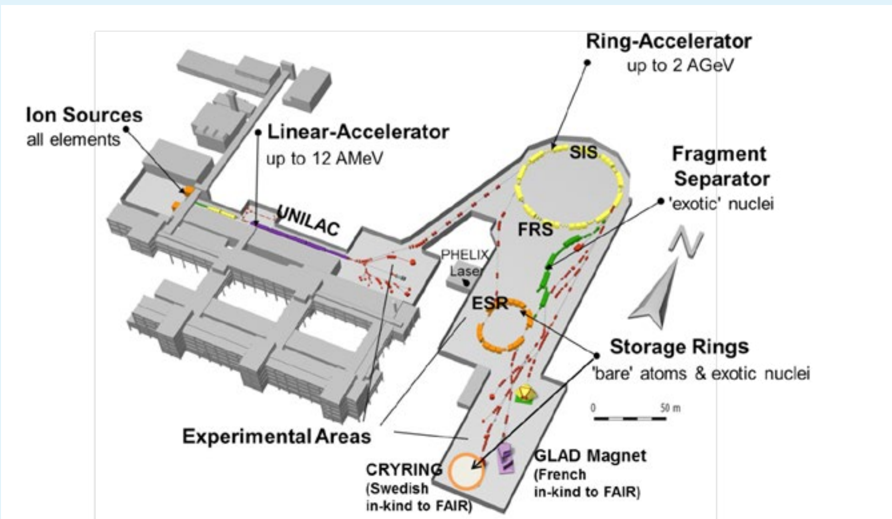
Equipment dedicated to nuclear structure and nuclear astrophysics research includes:

- Velocity filter SHIP for the separation and detection of super-heavy elements;
- SHIPTRAP, a Penning trap behind SHIP for nuclear structure and atomic physics studies on (heavy) nuclei/atoms;
- Gas-filled recoil separator TASCA with its ancillary setups for physics and chemistry studies;
- Multi-coincidence nuclear spectroscopy setup TASISpec, which can be coupled, e.g., to TASCA, SHIPTRAP but also other setups like JYFL-TRAP;
- Fragment separator FRS for the production an in-flight separation of exotic nuclei and experiments with isotopically clean or cocktail beams of elements ranging from protons up to Uranium; the FRS comprises a number of ancillary detectors, including spectroscopy of stopped beams;
- Storage-cooler ring ESR, equipped with powerful stochastic and electron cooling devices, Schottky mass as well as time-of-flight mass spectroscopy for mass measurements of short-lived nuclei, an internal gas-jet target, a collinear laser spectroscopy system and various X-ray and position sensitive particle detectors for in-ring (reaction) experiments;
- A suite of high-resolution Ge detectors for atomic and nuclear structure experiments;

By improving the performance of the ion sources and with other interventions, the primary intensity in the SIS18, which will serve as injector for the FAIR accelerators, was increased (e.g. from 5×10^8 Au ions/s to 5×10^9 Au ions/s); thereby new exotic nuclei have become accessible for experiments.

New opportunities for nuclear structure and astrophysics studies in the next 5 years include:

- New 28 GHz ECR ion source providing intense stable beams, e.g. for the heavy element programme at the UNILAC and the new cw-linac will become available;
- Development of a new cw-Linac specifically dedicated to the requirements of SHE research is ongoing; a first acceleration cavity ('demonstrator') is presently (2016) being commissioned and should be extended by further cavities to reach Coulomb barrier energies;
- In 2018 the GSI accelerators will be equipped with the FAIR accelerator control system, this will lead to an improved beam quality, better parallel operation, and a higher availability;
- The ALpha-BEta-GAmma (ALBEGA) detector setup for complete spectroscopy of chemically separated samples, a mobile setup for coupling, e.g., to recoil pre-separators;
- In 2018 the DEGAS Phase-1 array for decay studies of exotic nuclear beams. The set-up offers unprecedented sensitivity due to its active environment shielding.
- Commissioning of the R3B nuclear reaction set-up in 2017 with a new dipole magnet GLAD to study collective states and complete kinematics reactions with exotic nuclear beams;
- FRS Ion Catcher facility for experiments with thermalised and mass separated exotic nuclei for mass measurements, isomer studies, decay spectroscopy;
- CRYRING@ESR for storing, cooling and deceleration of Heavy Ions down to a few 100 keV/nucleon.



Schematic layout of the facility GSI, Darmstadt, Germany

Equipment/Projects dedicated to other/multidisciplinary research:

- Highly energy-efficient computing centre "Green IT-Cube" for data analysis and simulations for detector development and radiation safety;
- For atomic physics, the chain of trapping and storage facilities for heavy, highly-charged ions (HITRAP, CRYRING, ESR) all equipped with a broad variety of dedicated instrumentation;
- Experimental stations for atomic physics studies, channelling investigations with cooled ion beams extracted from the ESR, etc.);
- High power density beam bunches and various equipment for plasma physics research;
- Kilojoule/Petawatt Laser PHELIX including various (Laser light) beam lines to target areas allowing combined ion and laser beam experiments in plasma physics;
- Proton microscope PRIOR for radiographic imaging of dynamic systems with high spatial, temporal and density resolution;
- Experimental stations and a cell biology laboratory for research into the radio-biological effects of ion beams;
- Several experimental stations dedicated to materials research for irradiation experiments combined with in-situ characterisation: heavy ion microprobe allowing irradiations;
- Multipurpose/Test Stations, e.g. for tests of electronic components, or of detectors built for particle/nuclear physics and also for space missions.
- Fast 3D γ-scanner for the characterisation of radiation detectors and investigation of the internal structure of opaque objects.

New opportunities for other/ multidisciplinary studies in the next 5 years:

Through a collaboration between GSI and ESA, new users in the field of space radiation research have been attracted to GSI adding new fields of research like biophysics and radiation biology.

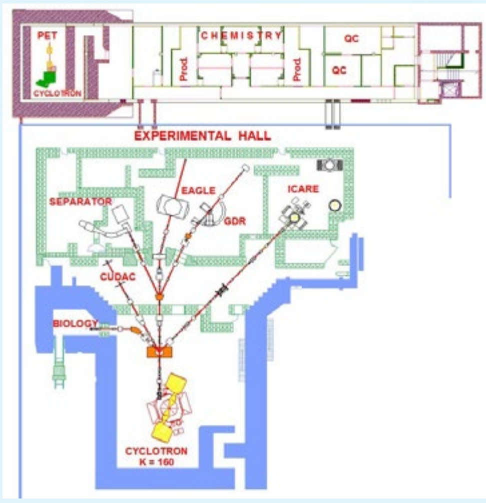
Multi-cavity advanced demonstrator based on superconducting cavities would not only serve super-heavy element research but applied research in materials science and biophysics as well.

HIL, Warsaw, Poland

The Heavy Ion Laboratory (HIL) of the University of Warsaw (www.slcj.uw.edu.pl) runs two cyclotrons – a heavy ion U-200P of K=160 equipped with the two ECR ion sources, accelerating beams from He to Xe up to an energy of 10 MeV/A, and a PETrace, K=16.5, delivering high intensity proton and deuteron beams. Since 1994 HIL has been an effective "user facility", serving up to the present time several hundred scientists from Poland and abroad. The research programme is mostly focused on low energy nuclear physics and its medical applications, including production of radio-isotopes.

Available instrumentation and set ups include: i) the EAGLE array – a γ-ray spectrometer, which can be easily coupled to ancillary detectors like an internal conversion electron spectrometer, a charged-particle 4π multiplicity filter (Si-ball), a scattering chamber equipped with up to 110 PIN-diode detectors, a 60-element BaF_2 gamma-ray multiplicity filter, a sectored HPGe polarimeter and plunger; ii) ICARE - a charged particle detector system used for reaction studies; iii) CUDAC – a PIN-diode array particle detection system; iv) SEPARATOR – a Scandinavian type on-line magnetic separator; v) GDR – a multi-detector system consisting of a large NaI(Tl) crystal with passive and active shields and a 32-element multiplicity filter.

Since 2012 the Radiopharmaceuticals Production and Research Centre, a division of HIL, has focused on the production of and research on Positron Emission Tomography radiopharmaceuticals. The production of longer-lived radioisotopes for life-sciences applications is also carried on.



Schematic layout of the facility HIL, Warsaw, Poland

Being a university unit HIL is in a natural way involved in teaching. In the coming years efforts will be focused on:

1. improving the transmission of the U200P cyclotron in order to get higher beam intensities.
2. construction of a capillary line connecting the PETrace cyclotron with the ECR ion source of the U200P in order to accelerate radioactive beams of ^{11}C, ^{15}O and ^{18}F.

IFIN-HH, Bucharest-Magurele, Romania

IFIN-HH, or the "Horia Hulubei" National Institute for Physics and Nuclear Engineering, located in Bucharest-Magurele (http://www.ifin.ro), is dedicated to research and development in physical and natural sciences, mainly Nuclear Physics and Nuclear Engineering, and in related areas including Astrophysics and Particle Physics, Field Theory, Mathematical and Computational Physics, Atomic Physics and Physics of Condensed Matter, Life and Environmental Physics. In all these fields, IFIN-HH conducts theoretical and experimental research. It has currently 3 tandem accelerators of 9, 3 and 1 MV maximum voltages and a cyclotron delivering proton beams up to 19 MeV. The latter 3 accelerators were installed in 2012 and are dedicated mostly to Nuclear Physics applications. The 9 MV pelletron tandem was completely modernized in the last decade and is mostly used for basic nuclear physics research. The "niche" of it is the measurement of lifetimes of nuclear states. A wide range of such lifetimes was covered, from tens of femtoseconds by using the Doppler Shift Attenuation Method, to picoseconds using the RDDS method and to nanosecond range using the newly developed in-beam fast-timing method. The basis is a multi-detector setup dedicated to γ-ray spectroscopy studies ROSPHERE (ROmanian array for SPectroscopy in HEavy ion REactions), consisting of a total of maximum 25 detectors of two types: Compton suppressed HPGe detectors and fast $LaBr_3$(Ce) scintillator detectors. It is a powerful instrument for lifetime measurements using the in-beam Fast Electronic Scintillation Timing (FEST) method or, together with a state of the art plunger device, using the Recoil Distance Doppler Shift (RDDS) method. If the experiment requires high resolution and high efficiency, ROSPHERE can be operated as a full HPGe array.

Picture of the γ-ray spectroscopy setup ROSPHERE IFIN-HH, Bucharest-Magurele, Romania

At the 3 MV tandetron in addition to applications of nuclear techniques in the physics of materials and the characterisation of cultural heritage artefacts, direct measurement for nuclear astrophysics are made, using prompt spectroscopy or activation techniques. The sensitivity of the latter is being enhanced by the use of IFIN-HH's ultralow background laboratory in the Slanic salt mine. The 1 MV tandetron is dedicated to AMS and is the basis for the internationally accredited RoAMS radiocarbon dating laboratory. The 3 tandem accelerators are open access facilities and their activity is guided by an international PAC which meets once or twice a year.

The TR19 cyclotron is the source for a Center of Radiopharmaceutical Research. The industrial size irradiator IRASM is being used for the irradiation of medical devices, materials and cultural artefacts.

ILL, Grenoble, France

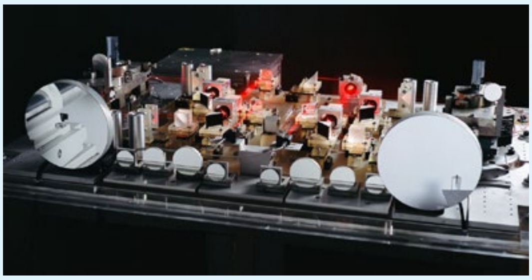
The Institut Laue-Langevin is an international research centre at the leading edge of neutron science and technology. ILL provides scientists with a very high flux of neutrons feeding some 32 state-of-the-art instruments, which are constantly being developed and upgraded. ILL covers nuclear and particle physics with a fraction of 5 instruments.

Every year, some 1400 researchers from over 40 countries visit the ILL. Research focuses primarily on fundamental science in a variety of fields: condensed matter physics, chemistry, biology, nuclear physics and materials science, etc.

ILL can specially tailor its neutron beams to probe the fundamental processes that help to explain how our Universe came into being, why it looks the way it does today and how it can sustain life.

Some instruments are entirely dedicated to nuclear physics and others can be shared for nuclear physics applications. Most of ILL's nuclear physics instruments are worldwide unique.

The fission fragment separator LOHENGRIN is a high resolution recoil separator for fission fragments produced by thermal neutron (with a flux of 5×10^{14} $cm^{-2}s^{-1}$). LOHENGRIN provides excellent selectivity,



Picture of the GAMS ultrahigh resolution gamma ray spectrometer with the laser interferometer at ILL, Grenoble, France

thus even very exotic ternary fission fragments like the halo nuclei ^{11}Li and ^{14}Be are clearly identified with yields as low as 10^{-10} per fission. This area is surrounded by clover Ge detectors. The mass-separated radioactive ion beams are also used for decay spectroscopy of fission products. The setup (including Si and neutron detectors) is particularly efficient for the study of microsecond isomers ($T_{1/2}$>0.5 μs).

The GAMS crystal spectrometer for gamma spectroscopy with ultrahigh resolution uses Bragg diffraction (with the angles monitored by laser interferometers) on one curved or two flat Si or Ge crystals. Summing all measured energies of a gamma-ray cascade after thermal neutron capture provides the neutron binding energy to the neutron mass determination together with Penning trap mass measurements of the proton and the deuteron.

The STEREO experiment probes the existence of light sterile neutrinos by measuring the evolution of the electron antineutrino spectrum at short baseline (10 m) from the compact core of the ILL reactor.

The PF1B intense cold neutron beam with polarisation option is a multipurpose beam port providing an intense beam of cold neutrons (5 meV average energy) with a capture flux of 2×10^{10} $cm^{-2}s^{-1}$ over 20×6 cm^2. These beams are used for detailed studies of the free neutron decay, for magnetic moment measurements or specific observables in fission.

The EXILL campaign in 2012/13 was very successful and used a collimated beam of PF1B with a powerful Ge detector array (EXOGAM from GANIL, ILL clover detectors and GASP-LNL detectors and $LaBr_3$:Ce fast timing detectors of the FATIMA collaboration) respectively.

The S18 thermal neutron interferometer is used for various quantum mechanics experiments with neutrons, and for high precision measurements of coherent neutron scattering lengths.

Ultracold neutrons (UCN) with energies below 250 neV are available at the ILL instruments PF2, SUN and GRANIT. UCNs at ILL provide most precise measurements of the free neutron's lifetime, the most precise limit for the electric dipole moment. UCNs at ILL are the only ones so far capable to study precisely quantum states of neutrons in the gravitational field with limits for hypothetical gravity-like interactions.

The V4 high flux irradiation position provides the highest neutron flux, up to 1.5×10^{15} $cm^{-2}s^{-1}$. Samples are activated to produce longer-lived radioisotopes at very high specific activity. These serve for nuclear medicine and other applications (e.g for targets of n_TOF@CERN and for the ECHo and HOLMES electron-neutrino mass experiments).

The very successful campaign of (n,γ) and (n,f) experiments with EXILL led to the creation of the new instrument FIPPS. It consists of a new germanium detector array with a large efficiency, which carries out high resolution gamma-ray spectroscopy (in multi coincidence), combined with a dedicated gas-filled spectrometer that can identify the second fragment with a large acceptance. The spectrometer is based on a new concept combining a gas-filled magnet and a time-projection chamber for individual 3D tracking of the fragments. The angular acceptance of the spectrometer can therefore be maximised without compromising the mass resolution. This unique instrument, in combination with the TOF measurement, will allow the mass and kinetic energy of the second fission fragment to be identified.

ISOLDE, CERN, Switzerland

ISOLDE is the CERN radioactive beam facility. The high energy, 1.4 GeV, and high average intensity of 2 μA of the proton beam on different thick targets produces high quality intense beams of rare isotopes. The accumulated target and ion-source knowledge allows the extraction and separation of more than 1000 different isotopes of 75 chemical elements; this is by far the highest number of isotopes available for users at any ISOL facility worldwide. A substantial fraction of the radioactive isotopes was accelerated up to 3 MeV/u with the REX-ISOLDE post-accelerator until 2012 and can be re-accelerated presently up to 5.5 MeV/u with a combination of the normal conducting REX-ISOLDE and the superconducting linac post-accelerator.

In order to broaden the scientific opportunities of the facility, the on-going HIE-ISOLDE (High Intensity and Energy) project was approved by CERN in September 2009 to provide major improvements in energy range, beam intensity and beam quality. The first stage boosting the beam energy of the post-accelerator to 5.5 MeV/u is fully operative delivering the first radioactive post-accelerated beams in September 2016. In the new energy regime the Coulomb excitation cross sections are strongly increased with respect to the previous 3 MeV/u and many transfer reaction channels become accessible. The second stage is expected to be completed for the start of 2018 and will allow energies of the beam up to 10 MeV/u for A/q = 4. ISOLDE offers thus the largest variety of post-accelerated radioactive beams near and above the Coulomb barrier in the world. The intensity and beam quality upgrade addresses many aspects that are implemented on a wider time scale.

Present experiments mainly deal with nuclear structure questions, explored via measurements of ground state properties (mass, radii, electro-magnetic properties), via decay studies or Coulomb excitation and transfer reaction studies. A sizeable part of the programme is devoted to other fields, such as nuclear astrophysics, and fundamental physics. Around 20% of the beam time is devoted to solid state physics and life sciences with broad societal benefits. An average of 50 different physics experiments are performed per year.

The facility includes two target-ion source units connected to a mass separator each delivering beams of radioactive nuclei to a dozen beamlines. The beamlines at the low energy part (beams of 30 - 60 keV) host permanent devices dedicated to ground state studies.

- Mass measurements are carried out at ISOLTRAP: a precision Penning-trap-based mass spectrometer. It also includes a multi-reflection time of flight (MR-TOF) spectrometer, used for mass measurements of very exotic beams and characterising the ISOLDE beam prior to measurements.
- Relative charge radii and electromagnetic properties are determined using CRIS/COLLAPS: laser spectroscopy experiments which probe the hyperfine properties of radioactive ions. CRIS is more sensitive while COLLAPS offers higher precision.
- Decay studies are served by IDS, the ISOLDE decay station, a polyvalent setup which can be used for all types of beta decay studies. Interchangeable setups allow for charged particle, beta and gamma spectroscopy. A recently added neutron detector array also allows neutron time of flight measurements to be performed. In addition, total absorption spectroscopy can be carried out at a dedicated setup (TAS).
- Nuclear orientation measurements can be performed at the NICOLE setup, a dilution refrigerator.
- Weak interaction studies to probe the existence of scalar currents, was first done with WITCH. Its upgrade, WISARD, will allow for the study of beta-delayed protons emitted in the decay of ^{32}Ar with the aim to reach a precision limit of 0.1% for the correlation coefficient "a" between positron and neutrino.

For applications, which range from materials science to biophysics there are numerous setups available:

Schematic layout of the ISOLDE Facility, Switzerland. The different parts of the Facility and experiments are indicated: the two target stations connected to the mass separators of low resolution, GPS and higher resolution, HRS.

- A dedicated beamline for applications (VITO) allows beta-NMR to be applied to biophysics, where liquid samples can be studied online.
- ASPIC houses an ultra-high vacuum chamber which allows for surface science experiments online.
- EC-SLI is an online setup for the measurement of emission channelling using short-lived isotopes in single crystal materials.
- Two beamlines are free for “travelling”systems.
- In addition two other beamlines are used for collections dedicated to studies of material science, biophysics or medicine.

A new building has been built in the northern part of the experimental hall hosting enlarged laser laboratories, a new dedicated laboratory for material science studies, and a new chemistry laboratory also used by biochemistry groups and in general open to the whole user community.

The post-accelerated beams have presently two operative beamlines. The first one hosts the high-resolution Miniball germanium detector array and the alternative ancillary detectors CD, T-REX and the new electron spectrometer SPEDE. A zero-degree spectrometer is also considered to ease the characterisation of the ejectiles. The second beamline is dedicated to reaction studies with the main focus on detection of the fragments.

With the present successful programme and on-going projects the number of users at ISOLDE is continuously increasing currently being of the order of 500 users per year. The member states are 16 and negotiations are ongoing with additional countries. ISOLDE leader of the ISOL method has been identified among others as future site for EURISOL.

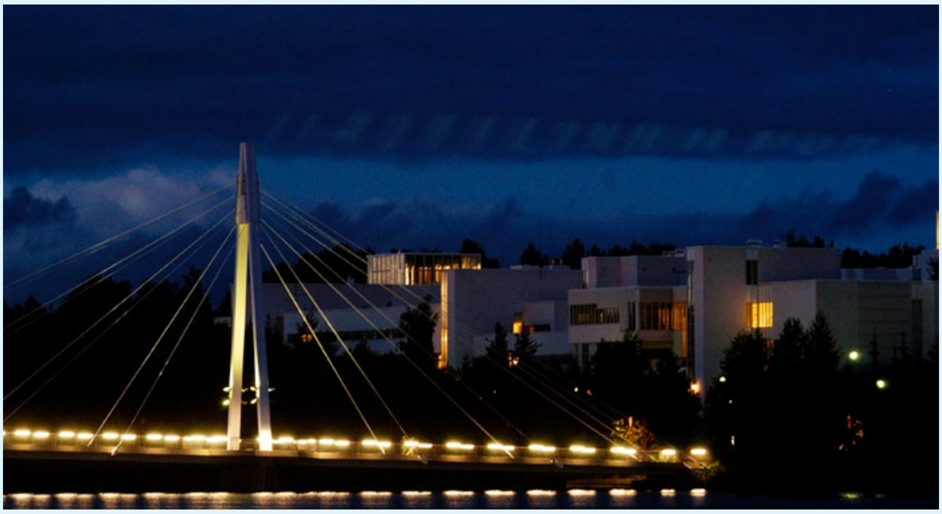
JYFL, Jyväskylä, Finland

The main accelerator facility of the Accelerator Laboratory of the University of Jyväskylä (JYFL) [www.jyu.fi/accelerator] consists of a K=130 cyclotron with three ECR ion sources and a multi-cusp ion source. The facility delivers a competitive range of stable-ion beams (from p to Au) suitable for modern nuclear physics research and applications, with total beam time of around 6500 hours a year.

JYFL is an access laboratory in Horizon2020 infrastructure projects and is an Academy of Finland Research Centre of Excellence. It has ~250 foreign users annually and foreign equipment investments. As a university laboratory it provides a unique training site for graduate students and young researchers.

Approximately one third of the K130 cyclotron beam time is dedicated to nuclear structure studies of proton drip line and superheavy nuclei. These studies have been mainly carried out using the RITU gas-filled recoil separator coupled to various arrays of silicon and germanium detectors at the target position and focal plane (JUROGAMII, SAGE, GREAT). These combinations represent one of the most versatile and efficient systems for in-beam and decay spectroscopy of exotic nuclei in the world.

At the IGISOL facility, exotic beams of both neutron-rich and neutron-deficient nuclei throughout the nuclear landscape are available for comprehensive studies of nuclear ground (and isomeric) state properties as well as exotic decay modes. These studies are driven by outstanding questions in nuclear structure, nuclear astrophysics and contributions to neutrino- and beyond-the Standard Model physics. Cooled and bunched radioactive ion beams are delivered to a versatile, complementary system of ion traps for high precision nuclear mass measurements, detector stations for decay



Picture of the laboratory JYFL, Jyväskylä, Finland

spectroscopy and optical spectroscopy for charge radii, nuclear spin and electromagnetic moment measurements.

The most important facility for applications is the RADiation Effects Facility (RADEF), which has been one of the three official test sites of ESA since 2005.

Future perspectives

The new MCC30 (K=30) light-ion cyclotron and the extension of the laboratory provide improved research conditions and additional beam time for all research teams and users. More time can be released for beam development and for the use of heavy-ion beams from the K=130 accelerator in longer experiments and tests.

The newly extended IGISOL-4 facility, served by both cyclotrons, offers a considerable improvement in discovery potential to unexplored exotic nuclei with readily accessible increase in beam time (K=30 cyclotron) for the most challenging of cases. An expansion of infrastructure sees new tools and techniques for mass measurements, including a Multi-Reflection Time-of-Flight Mass Spectrometer and the implementation of Phase-Imaging Ion Cyclotron Resonance measurements. A number of laser systems are available for laser ionisation and spectroscopy applications, as well as for high-resolution collinear laser spectroscopy. New atom and ion trapping systems are under development. Higher intensity light ion primary beams as well as developments for neutron-induced fission will push the facility to the most exotic of fission fragments.

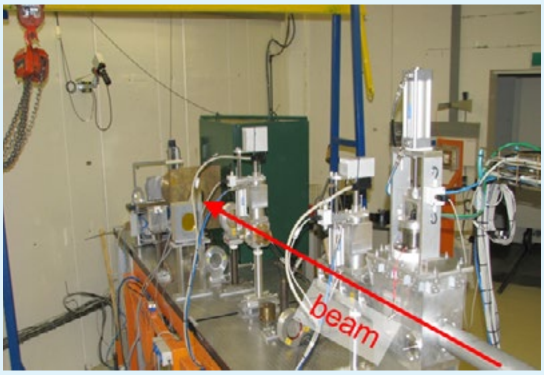
The recently commissioned MARA recoil mass spectrometer will further extend the possibilities to study the structure of proton drip line nuclei in in-beam and decay spectroscopic studies.

As with the RITU gas-filled recoil separator, MARA will be coupled with the various arrays of silicon and germanium detectors, such as the JUROGAMIII array. MARA will enable further investigation of topics such as isospin symmetry and pairing in N=Z nuclei.

In order to fully exploit the potential of the new MARA mass separator, researchers from JYFL-ACCLAB are preparing for a new low-energy facility at MARA. This will see the installation of a gas cell at the MARA focal plane, coupled with laser systems for selective ionization and spectroscopy. In a second phase, low-energy beams from MARA will be delivered to a cooler-buncher and MR-TOF mass spectrometer.

KVI-CART, Groningen, The Netherlands

The KVI-Center for Advanced Radiation Technology (KVI-CART) [http://www.rug.nl/kvi-cart/] at the University of Groningen is the only scientific accelerator laboratory in the Netherlands.



Setup for radiobiology experiments at KVI-CART, Groningen, The Netherlands

The central facility is the superconducting cyclotron AGOR (K=600) which delivers protons of up to 190 MeV energy and heavier ions up to Pb. The maximum energy of the heavy ion beams ranges from 90 MeV per nucleon for e.g. ^{12}C and ^{16}O to about 15 MeV per nucleon for ^{208}Pb. The KVI-CART facilities are under certain conditions open to an international user community.

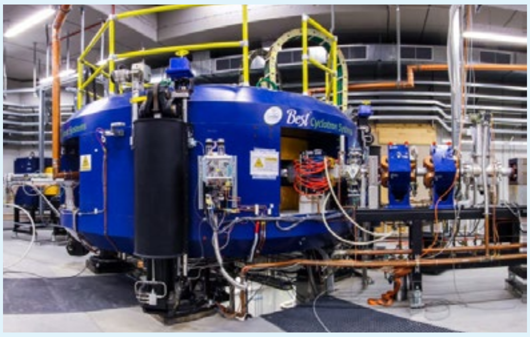
The AGOR accelerator facility is mainly used for radiation physics, materials science, ion beam analysis and radiation biology research and for commercial radiation hardness testing using both proton and heavy ion beams. KVI-CART has a vital research programme on physics, technology and radiobiology for particle therapy together with the university medical center (UMCG) and other partners related to the clinical proton therapy facility at UMCG.

The expertise of KVI-CART in accelerator and radiation physics and radiation protection is frequently called upon by industry.

The nuclear and hadron physics group of KVI-CART is performing its research in the frame work of the NuSTAR and PANDA collaborations at the new FAIR facility in Darmstadt and is participating in the BESIII-experiment at the BEPC accelerator (Beijing). KVI-CART is also contributing to the design and construction of the SuperFRS separator at GSI-FAIR.

LNL, Legnaro, Italy

LNL is one of the four national facilities funded by INFN with the mission of providing infrastructures for nuclear physics research for Italian and foreign users. The area of main interest is on nuclear structure and reaction dynamics, using heavy ion beams provided by the 15 MV Tandem and by the ALPI superconducting LINAC, the latter used either coupled to the Tandem or to the heavy ion injector PIAVE. Applied and interdisciplinary physics is also an important activity, making use



Picture of the proton cyclotron for the SPES project at LNL, Legnaro, Italy

mainly of beams delivered by the 7 MV CN and 2 MV AN2000 accelerators. Nuclear structure and reaction dynamics studies are performed at bombarding energies close to the Coulomb barrier and are based on dedicated instrumentation, which include large arrays of gamma-ray detectors, magnetic spectrometers and particle detector arrays. In nuclear spectroscopy investigations are being performed on high spin physics, nuclear structure at finite temperature, symmetry properties of nuclei, shell stabilisation and quenching, both on the proton rich and neutron rich side of the nuclear chart. Studies of reaction mechanisms are mainly focused on near and sub-barrier fusion reactions, elastic, inelastic and multi-nucleon transfer, break-up and clustering processes, nuclear matter behaviour in finite systems.

The main installed detectors, making use of the heavy ion beams from the TANDEM-ALPI-PIAVE complex are :

GALILEO: a conventional gamma-ray detector array composed of 40 HPGe detectors with their BGO anti-Compton shields and 30 cluster capsules re-assembled at LNL in 10 new triple cryostats surrounded as well by re-assembled BGO scintillators to get high photopeak efficiency. GALILEO takes advantage of the recent technical developments made within the AGATA collaboration and the integration with different ancillary devices such as light charged particle detectors (EUCLIDES, TRACE), heavy fragments detectors (DANTE, RFD), neutron detectors (NW, NEDA) and plunger devices.

GARFIELD: a 4π-array for the detection of light charged particles and heavy fragments emitted in heavy ion collisions. It consists of 2 two large volume drift chambers employing micro-strip gas devices as ΔE stage, complemented by CsI(Tl) scintillators as residual energy detectors. At forward angles a highly segmented annular three stage telescope is used. The whole apparatus is equipped with fully digital electronics read-out. Within the same framework there is an intense activity related to the construction of the new particle detector array FAZIA.

PRISMA: a very large solid angle spectrometer and devoted to the measurement of experimental observables of nuclei produced in multi-nucleon transfer reactions. Its performance in terms of efficiency and resolution has been demonstrated during the 10 years of operation, also in conjunction with the CLARA and AGATA Demonstrator γ-arrays. The spectrometer is presently used in kinematic coincidence with a second time-of-flight system based on gas detectors. Transfer reactions are closely connected with near and sub-barrier fusion reactions, which are studied with the electrostatic beam separator and time-of-flight system PISOLO.

Among other available experimental set-ups, is the EXOTIC apparatus, an in-flight facility for the production of secondary radioactive light-ion beams following inverse kinematics reactions induced by light stable beams on gas targets. Moreover, the LIRAS set-up is dedicated to the study of resonances of astrophysical interest and cluster structure in light-ion reactions.

The present detectors with their ongoing upgrades and couplings to the “itinerant” detectors (AGATA, FAZIA and NEDA), will be shortly employed in a wide range physics programme making use of the unstable beams delivered by the SPES facility and reaccelerated with the ALPI Linac.

With the long term goal to study parity non-conservation effects in heavy alkalis and finding possible deviations from standard model predictions, a research programme is being carried out to study atomic transitions in Fr isotopes produced via fusion evaporation reactions and delivered to a magneto-optical trap.

Important activities are carried out in the field of nuclear reactions of astrophysical interest, in particular with the BELINA neutron time-of-flight system at the CN accelerator and other dedicated set-ups at the AN2000. Moreover, at these small accelerators, ion beam analysis like characterisation of materials via Rutherford backscattering or micro-pixe are presently used.

Research is also made at LNL on radio-biological effects, with applications in the study of cellular and molecular response to radiation.

The research in the accelerator field is mainly focused in the development and construction of high power RFQ for high intensity proton beams for the IFMIF and ESS projects, carried out within wide international collaborations, among which EURISOL-DF.

LNS, Catania, Italy

The Laboratori Nazionali del Sud (LNS) in Catania are one of the four national laboratories of INFN. Research is mainly carried out in the field of Nuclear Physics, Nuclear Astrophysics and Particle Astrophysics, as well as in many interdisciplinary fields, like application of Nuclear Physics to Medicine and to Cultural Heritage, and Accelerator Physics.

Two accelerators, a 15 MV Tandem and a K=800 Superconducting Cyclotron (CS), are fully operating, providing ion beams from H to Pb, with energy from 0.1 to 80 MeV per nucleon. With the FRIBS@LNS facility, radioactive ion beams have been available for more than 10 years by applying the in-flight fragmentation method, the primary beam being provided by the CS. Tagging detectors allow to identify secondary fragments, used as projectiles in many nuclear physics experiments.

Stable and radioactive beams can be transported to several experimental halls, equipped with detection apparata and scattering chambers. The most sophisticated and powerful experimental apparata are:

CHIMERA, a 4π detector complex consisting of about 1200 telescopes, able to identify ions in a wide range of masses. It is mainly used for studies of multifragmentation, but its large solid angle makes it particularly suited for experiments with low intensity radioactive beams

MEDEA-SOLE-MACISTE, a complex made of 180 BaF_2 scintillators, a superconducting solenoid and a focal plane detector, jointly operated to detect γ rays, light and heavy fragments at forward angles. The system is particularly suited to study GDR and pre-equilibrium processes at intermediate energies

MAGNEX, a large acceptance magnetic spectrometer, specifically designed for experiments with radioactive beams. It is now used to perform a broad physics programme covering different research lines.

Picture of the upper part of the superconductor cyclotron at LNS, Catania, Italy

Since 2002 the LNS have been hosting the center for proton therapy of ocular tumors (CATANA), which currently numbers 350 patients treated with a success percentage of 95%. The LNS are also engaged in the study of clinical applications of proton beams accelerated in the plasma produced by the laser-matter interaction. In particular, the construction of a hall for preclinical treatment in Prague, as a part of the European infrastructure ELI, has been assigned to the LNS.

The LNS contribute to the construction of the European Spallation Source (ESS) in Lund, coordinating the INFN activities related to the ion source, the LEBT, the Drift Tube Linac and the superconducting cavities.

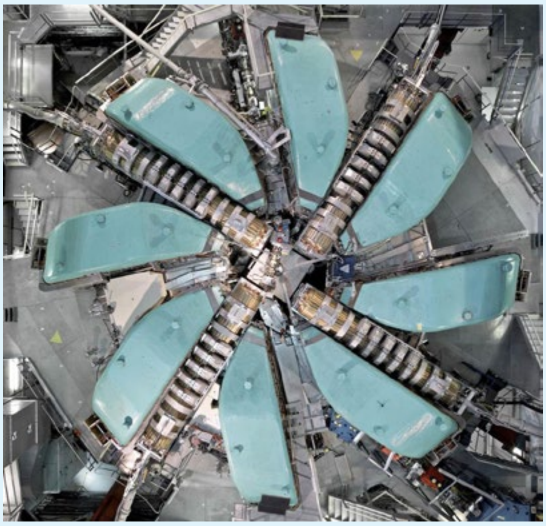
Several laboratories are operative at the LNS: the Landis laboratory for applications of Nuclear Physics in the field of cultural heritage, the laboratory of Environmental Radioactivity, the laboratory of Radiobiology.

At the LNS a research infrastructure has been realised for the detection of high energy astrophysical neutrinos at large depths (KM3NeT). It consists of two laboratories located at the port of Catania and in Portopalo di Capopassero. This infrastructure is also used in other fields of science, i.e. geophysics, volcanology, earth science, marine biology.

The LNS K800 Superconducting Cyclotron (CS) is being upgraded. The demand for intense beams with mass A<40 and power of 2-10 kW comes from several experimental proposals aiming to the study of rare processes. One of them aims to determine the Nuclear Matrix Elements of Neutrinoless Double Beta Decay through the study of double charge exchange reactions. Furthermore, with this upgrade new experiments with radioactive beams of the FRIBS@LNS facility will be feasible. The planned experiments concern the study of the isospin physics and of light neutron and proton rich nuclei beyond the drip lines.

PSI, Villigen, Switzerland

PSI offers several user facilities. The high intensity proton accelerator (HIPA) at PSI started operation in 1974 and soon outperformed its design current, today by more than a factor of 20. Protons of 590 MeV efficiently produce low momentum pions, decaying subsequently to muons (and electrons). HIPA has been consequently maintained and upgraded over the years. Today it is leading the high-intensity frontier with its continuous 1.4MW beam power. It can routinely deliver 2.4mA (50MHz, quasi-DC), run 8 months per year and deliver the world's highest intensity low momentum pion and muon beams for fundamental and applied physics. On the fundamental physics side, the muon beams



Picture of the HIPA ring cyclotron at PSI, Villigen, Switzerland

have been used to obtain the strongest limits on all three golden charged lepton flavour violating channels, $\mu \to e\gamma$, $\mu \to eee$ and $\mu \to e$-conversion on nuclei. Exotic atom physics is another key component of the research programme ranging from muonium, via pionic hydrogen to extract πN scattering length benchmarks, to light muonic atom laser spectroscopy and precision extraction of charge and magnetic radii of the proton and other light nuclei. Also the determination of charge radii of heavy isotopes is coming back into focus, especially for certain radioactive isotopes, e.g. radium. Muons and light muonic atoms are also being used for weak interaction studies, the most precise muon lifetime measurement to determine the Fermi coupling constant of weak interaction, the most precise measurement of muon capture on the proton to determine the pseudoscalar coupling constant and on the deuteron to test low energy QCD and effective theories in a process similar to pp-fusion in the sun.

HIPA, since 2011, also drives a high-intensity source for ultracold neutrons serving the world's leading search for the neutron electric dipole moment (nEDM) and offering a total of 3 beam ports for experiments. The nEDM sensitivity is also being exploited to search for Dark Matter in form of axion-like particles and for tests of symmetries and exotic interactions.

Beams of protons, pions and electrons are also used for irradiation applications. At the spallation neutron source SINQ, several irradiation options exist and a leading neutron radiography and tomography is in place. The main proton irradiation facility, PIF, uses protons of variable energy from the medical cyclotron for electronics component testing in times when the beam is not needed for the tumour treatment of patients. For the latter, PSI has three gantries and one eye tumour treatment place. Mainly at the injector cyclotron, various isotopes are being produced, also for preclinical studies and radiopharmaceutical applications. Activated materials are being processed by the Laboratory of Radiochemistry to extract important rare isotopes, e.g. as targets for various nuclear physics experiments world-wide.

FUTURE RESEARCH INFRASTRUCTURES

ESFRI Roadmap Facilities

ELI-NP, Bucharest, Romania

The Nuclear Physics pillar of the Extreme Light Infrastructure European Project (ELI-NP) is located in the Magurele Physics Research Campus, near Bucharest. As part of the Extreme Light Infrastructure Project, ELI-NP was included on the 2006 ESFRI Roadmap and since 2016 is listed as an ESFRI landmark research infrastructure.

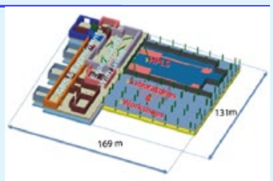
The implementation of ELI-NP is performed by the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) in the period 2013-2018.

The major research equipment at ELI-NP able to deliver unique beams with beyond state-of-the-art features world-wide comprises:

- A very high power laser system (HPLS), with two 10 PW ultra-short pulse lasers able to reach intensities of 10^{23} W/cm^2 and electrical fields of 10^{15} V/m.
- A high brilliance gamma beam system (GBS) able to deliver quasi-monochromatic linearly polarised beams with energies up to 19.5 MeV by following the incoherent Compton backscattering of laser light off a very brilliant, intense, relativistic electron beam produced by a warm RF linac.

At the end of the first implementation phase (2013-2015), the components of the first 10 PW laser in the world have been finalised along with the first part of the gamma beam system. Working groups of international scientists, coordinated by the ELI-NP physics team, finalised the Technical Design Reports containing the main instrumentation needed for experiments at ELI-NP. The reports were approved by the International Scientific Advisory Board and are presently being implemented.

The second phase of the project (2016-2018) was approved by the European Commission



Picture and schematic layout of the ELI-NP infrastructure at Bucharest, Romania

and is currently under implementation. In 2019 the infrastructure will be operational in all its components.

The use of the very high intensity lasers and the very brilliant γ-beams will allow approaching a field of science not yet explored at the frontier between laser, plasma and nuclear physics. In particular, major progress will be achieved in expanding the scientific horizon of nuclear physics and associated fields:

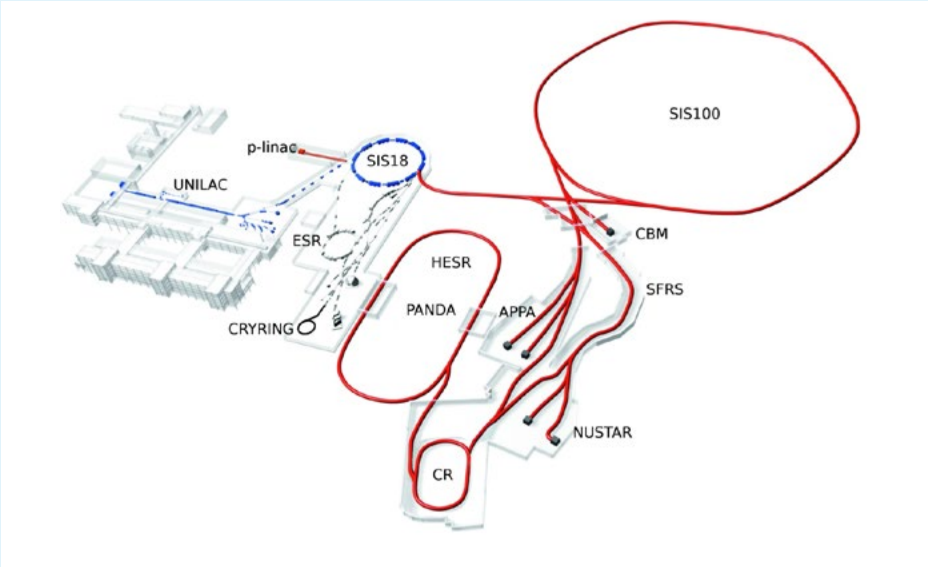
- Investigation of the high-power laser-matter interactions using nuclear physics methods in order to study the possibilities of obtaining proton and heavy ion accelerated beams using lasers.
- The extremely high intensity of the laser beam will allow for the study of fundamental physics phenomena anticipated by theory, such as vacuum birefringence and pair creation in intense electric fields.
- Investigation of nuclear structure and cross sections of interest for astrophysics using photonuclear reactions.
- New methods of identification and remote characterisation of nuclear materials will be investigated with application for homeland security and nuclear material management.
- New ways of producing more efficiently radioisotopes currently used in medicine and the production of newly proposed ones.
- Simultaneous use of the high intensity gamma and laser beams will enable fundamental physics studies as pair production in vacuum.

FAIR, Darmstadt, Germany

The Facility for Antiproton and Ion Research, FAIR, in Darmstadt, Germany, will provide world-wide unique accelerator and experimental facilities allowing for a large variety of unprecedented forefront research in physics and applied science. Nine countries plus one associated are currently participating in this project. It is the largest basic research project on the roadmap of the European Strategy Forum of Research Infrastructures (ESFRI), and is a landmark of the European Research Area. FAIR offers an abundance of outstanding research opportunities to scientists from all over the world.

FAIR is being planned by international partner institutions as a new large accelerator and research complex. The FAIR member states agreed to construct FAIR in a staged approach and defined a Modularised Start Version: a superconducting synchrotron SIS100 with a circumference of about 1,100 meters and magnetic rigidity of 100 Tm is at the heart of the FAIR accelerator facility. Following the upgrade for high intensities, the existing GSI accelerators UNILAC and SIS18 will serve as injectors. Attached to the large synchrotron SIS100 is a complex system of storage-cooler rings and experiment stations including a superconducting nuclear fragment separator (Super FRS) and an antiproton production target. FAIR will supply radioactive ion beams and antiproton beams with unprecedented intensity and quality. The FAIR design allows for future upgrade options including, among others, the installation of a second accelerator ring.

A rich and multidisciplinary research programme will be conducted covering a broad spectrum of research fields such as: QCD studies with cooled beams of antiprotons; QCD-Matter and QCD-Phase Diagram at highest baryon density; nuclear structure and nuclear astrophysics investigations with nuclei far off stability; precision studies on fundamental



Schematic layout of the FAIR facility, Darmstadt, Germany

interactions and symmetries; high density plasma physics; atomic and materials science studies; radiobiological investigations and other application oriented studies.

The baseline FAIR research programme includes 14 initial experiments, which form the four scientific pillars of FAIR (in alphabetical order):

- APPA: Atomic and plasma physics, and applied sciences in the bio, medical, and materials sciences.
- CBM: Physics of hadrons and quarks in compressed nuclear matter, hypernuclear matter.
- NuSTAR: Structure of nuclei, physics of nuclear reactions, nuclear astrophysics and radioactive ion beams (RIBs).
- PANDA: Hadron structure and spectroscopy, strange and charm physics, hypernuclear physics with antiproton beams.

Detectors and equipment for FAIR are being constructed by the international partners and have already been partly taken into operation. These detectors combined with the upgraded GSI accelerator chain will allow forefront experiments during the next years starting in 2018 until FAIR is operational (FAIR Phase 0). NuSTAR experiments will profit from the higher beam intensities and a start version of the R^3B experiment is being set up at the SIS18 and several new detectors will be exploited. In particular, the GLAD dipole magnet, a French in-kind contribution, will become operational. The low energy storage ring CRYRING, a Swedish in-kind contribution to FAIR, was installed at GSI and successfully commissioned with beam from the Experimental Storage Ring ESR. This facility offers research opportunities for atomic physics and nuclear astrophysics experiments with stored and cooled low energy heavy-ion beams. The nuclear matter and hadron physics community will profit from the higher beam quality and intensities available for experiments with an upgraded HADES detector also testing PANDA and CBM detector components. This programme in Darmstadt will be supplemented by the participation of the CBM and PANDA collaborations elsewhere, e.g. CBM will contribute to the low energy beam scan at RHIC and fixed target experiments at the Nuclotron, and the PANDA collaboration will participate in experimental campaigns at BELLE, BES3, and JLAB. Newly developed CBM and PANDA detector components will be exploited and will enhance existing experimental set-ups.

NICA, Dubna, Russia

The NICA (Nuclotron-based Ion Collider fAcility) project is now under realisation at the Joint Institute for Nuclear Research (JINR). The main goal of the project is extension of the existing relativistic ion facility Nuclotron – to the world level research infrastructure facility. NICA aimed at the study of hot and dense nuclear and baryonic matter in heavy ion collisions and spin physics research at polarised proton and deuteron beams. The centre-of-mass energies up from 4 to 11 GeV per nucleon will be available in heavy ion research mode. Polarised proton collisions can be studied over energy range up to 27 GeV. The facility operation in a collider and fixed target modes are foreseen. Physics detector setups MPD, SPD and BM@N are under design and construction. An average luminosity in the collider mode is expected to $1{\cdot}10^{27}$ cm^{-2} s^{-1} for Au^{79+} collisions. Extracted beams of various nucleus species with maximum momenta of 13 GeV/c (for protons) will be available.

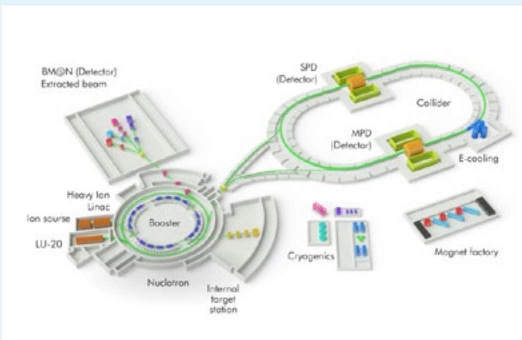
The proposed programme is aimed at obtaining new data and knowledge that should shed light on: in-medium properties of hadrons and the nuclear matter equation of state (EOS); the onset of deconfinement (OD) and/or chiral symmetry restoration (CSR); phase transition (PT), mixed phase (MP) and the critical end-point (CEP); possible local parity violation (LPV) in strong interactions. The NICA research domain is attractive as being the expected region for searching of new phenomena at the maximum baryon density including possible phase transitions.

The study of the nucleon spin origin ("spin puzzle") and polarisation phenomena in light polarised ion interactions is another target of the research. The high intensity and polarisation (>50%) of colliding beams could provide unique possibilities for this study.

The particle beams of the NICA complex will be used not only for fundamental research but also for innovation and technological activities.

This research infrastructure will be able to give opportunities for investigations to about 1000 visitors, scientists and engineers working in accelerator, particle and nuclear physics as well as in applied researches with use of the accelerator technique (medicine, new materials, micro electronics, etc.).

The BM@N aimed at several goals: in heavy-ion (A+A) collisions these are: study of the dense nuclear matter with strangeness including: a) production mechanisms and modifications of hadron properties in dense nuclear matter using the following probes: strange mesons, strange and multi-strange baryons; vector mesons via hadronic or dilepton/photon mode); b) study of the EoS with strangeness, c). hyper-matter production: search for light hypernuclei and multi-strange metastable objects; study of elementary reactions: pp, pn(d) as "reference" to pin down nuclear effects; search for ‚cold' nuclear matter with pA – collisions.



Schematic layout of the NICA complex at Dubna, Russia

The MPD experimental programme is aimed to investigate both hot and dense baryonic matter and polarisation phenomena. A preliminary list of the first priority physics tasks to be performed includes:

- measurement of a large variety of signals at systematically changing conditions of collision (energy, centrality, system size) using as bulk observables 4π geometry particle yields (OD, EOS); multi-strange hyperon yields and spectra (OD, EOS); electromagnetic probes (CSR, OD); azimuthal charged-particle correlations (LPV); event-by-event fluctuation in hadron productions (CEP); correlations involving π, K, p, Λ (OD); directed and elliptic flows for identified hadron species (EOS,OD); reference data (i.e. p + p) will be taken at the same experimental conditions;
- study of hyperon polarisation and other polarisation phenomena including possible study of the nucleon spin structure via the Drell-Yan (DY) processes after the MPD upgrade.

The evaluated rate in Au + Au collisions at the maximum energy (10% central interactions) will be up to 7 kHz taking into account the design luminosity of $L = 1{\cdot}10^{27}$ cm^{-2} s^{-1}.

The main processes, which could be studied with the SPD are the following:

- DY and *J/ψ* production processes with longitudinally and transversally polarised p and d beams for extraction of unknown and poorly known parton distribution functions (PDF);
- Direct photon production in the hard processes for an access to the gluon polarisation of the nucleon;

All PDFs can be measured in one experiment. It will be possible also to investigate: spin effects in various exclusive and inclusive reactions; cross sections of diffractive processes; helicity amplitudes and double spin asymmetries (Krisch effect) in elastic reactions. This can be performed in the kinematic region not available for other experiments.

SPIRAL2, Caen, France

SPIRAL2 is a new European facility to be built at GANIL in Caen, France. The project aims at delivering stable and rare isotope beams with intensities not yet available with present machines. SPIRAL2 together with FAIR will reinforce the European leadership in the field of nuclear physics based on exotic nuclei and as such was selected in 2006 on the ESFRI roadmap and recognised in the 2016 edition of this roadmap as a landmark European facility.

The first phase of the SPIRAL2 facility is under commissioning and it consists of a high power, CW, superconducting LINAC, delivering up to 5mA of protons at 33 MeV and deuterons at 40 MeV (200 kW) and up 1mA of heavy-ions at 14.5 MeV/nucleon. The heavy-ion beams will be used to produce in-flight nuclei with the Super Separator Spectrometer (S3), neutron-deficient exotic nuclei and very heavy nuclei via fusion evaporation reactions, or light neutron rich nuclei via transfer reactions. The low energy (few keV/nucleon) exotic nuclei produced at S3 and at the existing SPIRAL1 facility will be studied in the new experimental hall called DESIR. The high neutron flux produced with the deuteron beam at the Neutron For Science facility (NFS) will open a broad new field of research at GANIL with unique experimental possibilities for applications and reliable nuclear data evaluation.

In the second phase of the project production of the radioactive nuclear beams will be based essentially on the fast neutron induced fission of the uranium target using ISOL technique. The expected radioactive ion beams intensities in the mass range between A=60 and A=140, reaching up to 10^{10} particles per second for some species, will be unique in the world. These unstable beams will be available at energies ranging between a few keV/nucleon at the DESIR facility up to 20 MeV/nucleon (up to 9 MeV/nucleon for fission fragments) at the existing GANIL experimental areas, which will be enriched by a large number of next generation detectors such as AGATA, PARIS and EXOGAM2 gamma arrays, MUGAST/GASPARD and FAZIA-INDRA charged particle detectors/arrays, NEDA neutron detector and the ACTAR-TPC active target.

The main goal of SPIRAL2 is to extend the knowledge of the limit of existence and the structure of nuclei to presently unexplored regions of the nuclear chart, in particular in the medium and heavy mass regions. The scientific programme proposes the investigation of the most challenging nuclear and astrophysics questions aiming at the deeper understanding of the nature of matter. It also addresses many different types of applications of nuclear physics of interest to the society, such as nuclear energy and medicine, radiobiology and material science. This scientific programme, elaborated by a team of six hundred specialists from all over the world will contribute to the physics of nuclei far from stability, nuclear fission and fusion based on the collection of unprecedented high precision detailed basic nuclear data, to the production of rare radioisotopes for medicine, to radiobiology and to materials science. The SPIRAL2 project is also one of the pillars of EURISOL-DF (Distributed Facility), an intermediate and essential step towards the building of EURISOL, the most advanced nuclear physics research facility presently imaginable in the world based on the ISOL principle.

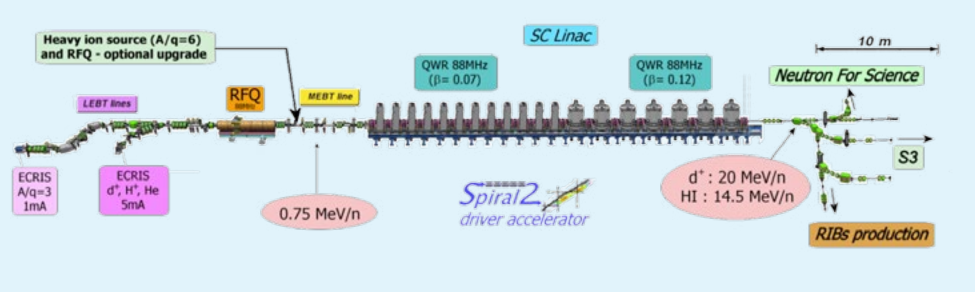
The current discussions with international partner countries would allow them to join the ongoing construction of the base-line project and associated detectors as well as the future operation phase, turning the present GANIL into a fully international legal entity. Up to now 15 MoUs, International Associated Laboratories (LIA) agreements have been signed with major laboratories, institutions and ministries world wide (Japan, China, India, US, EU,..). The transformation of GANIL with SPIRAL2 into an international facility is expected in the coming few years.

Timeline and status. The construction of SPIRAL2 began in 2005 and is separated into phases:

- Linear accelerator with S3 and NFS experimental halls – first experiments in 2017;
- DESIR low-energy RIB facility – construction from 2017, first experiments expected by 2020;
- A second heavy-ion injector for LINAC accelerating heavy ions with A/q ratio equal to 7 allowing an increase of the intensity of medium-mass and heavy beams – design study expected to begin in 2016;
- ISOL Radioactive Ion Beam production hall construction after 2021.

The GANIL-SPIRAL2 facility will be one of the main components of the forthcoming EURISOL-DF project, which has an ambition to enter the ESFRI roadmap.

In the longer-term future, secondary fragmentation of the SPIRAL2 rare isotope beams accelerated to energies greater than 150 MeV/nucleon would be



Schematic layout of the driver accelerator and beamlines leading to different instrumentation at Spiral 2, Caen, France

a natural evolution of the facility towards EURISOL.

The GANIL/SPIRAL2 facility will open a new avenue for the RIB physics in Europe. With its rich and multipurpose scientific programme, the SPIRAL2 project is not only a great promise for the nuclear physics community, it will also substantially increase the know-how of technical solutions to be applied not only for EURISOL but also in a number of other European/world projects.

http://pro.ganil-spiral2.eu/

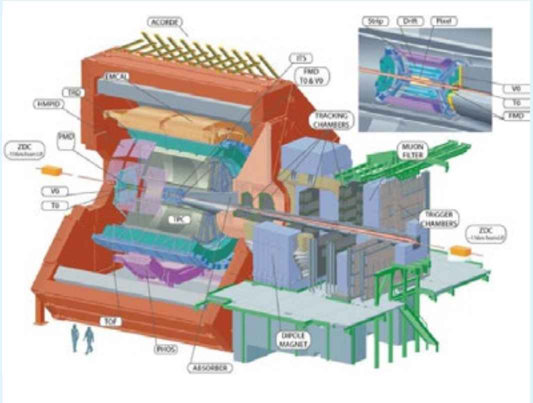
NEW FACILITIES AND MAJOR UPGRADES OF EXISTING FACILITIES

The ALICE Upgrade

ALICE is the LHC experiment, which is devoted to the study of the Quark Gluon Plasma (QGP). In particular, it is studying the deconfinement phase transition under conditions prevailing in the early Universe, i.e. at vanishing net baryon density. The ALICE detectors comprise two spectrometers, the central barrel covering mid-rapidity with excellent particle identification down to very low p_T as well as photon and jet capabilities and the muon spectrometer at forward rapidity providing muon detection.

Following first Pb-Pb, p-Pb and pp measurements at unprecedented energies during Run 1, the detector saw its completion and consolidation during Long Shutdown 1 and is currently set to accomplish the goal to accumulate 1 nb^{-1} of Pb–Pb collisions during Run 2, a factor of ten as compared to Run 1, along with comparable statistics for p-Pb and pp collisions.

The experiment has been approved for a major upgrade during Long Shutdown 2 (2019-2020). The upgrade aims at precision measurements of the QGP, with a factor 100 gain in inspected luminosity (a factor of 10 through an increase in luminosity and an additional factor of 10 via pipelined readout). Special emphasis will be put on low p_T physics with minimum bias triggers, with a unique focus on heavy flavour production and low-mass di-leptons. To this end a new, ultra-low mass silicon tracker will be placed around a beam-pipe with reduced diameter (∅ 34.4 mm), the TPC will be upgraded with GEM detectors for continuous (un-gated) readout, a new Muon Forward Tracker MFT (for muon vertexing) will be implemented, a new Fast Interaction Trigger FIT detector will provide trigger and multiplicity measurements, and the readout electronics of all subdetectors will be upgraded for continuous readout at 50 kHz interaction rate in Pb-Pb collisions. This goes in hand with an upgrade of the online systems to process



Schematic view of the ALICE setup with the different detector components at LHC CERN Switzerland

all of the events prior to archival. Furthermore, studies for a forward high granularity calorimeter are ongoing. This would allow unique saturation studies at very forward rapidities, i.e. at very small x_B.

Assuming a peak luminosity of $6x10^{27}$ $cm^{-2}s^{-1}$ and an average luminosity of $2.4x10^{27}$ $cm^{-2}s^{-1}$ for Pb-Pb collisions and ion operation for about one month per year, the currently anticipated physics programme for an integrated luminosity of 10 nb^{-1} in PbPb at full magnetic field and top energy, a special run at lower magnetic field (O ~ 3 nb^{-1}), further p-Pb running with about 50 nb^{-1} as well as pp reference running would take until Long Shutdown 4 (~ 2029).

The HIE-ISOLDE upgrade

The high energy, intensity and purity upgrade of the ISOLDE Facility is on going with the first stage of energy upgrade to 5.5 MeV/u operative since September 2016. The second stage of the energy upgrade that will boost the energy of the post-accelerated radioactive beams to 10 MeV/u includes also the installation of a third beamline that will be operative in 2017. The ISOLDE Solenoidal Spectrometer, ISS, for transfer reaction studies will be then housed on the second beamline, while the scattering chamber and the rest of movable setups approved for experiments at ISOLDE will be connected to the third beamline.

The third and final stage involves the manufacturing and installation of two more cryomodules, each housing six low-β (β_g = 6.3%) cavities and two superconducting solenoids. These accelerating elements will replace the present 7-gap resonators and 9-gap Interdigital H-type structure of REX and allow also for deceleration of the beam, providing access to a wider range of low energies. The third stage of the energy upgrade foresees

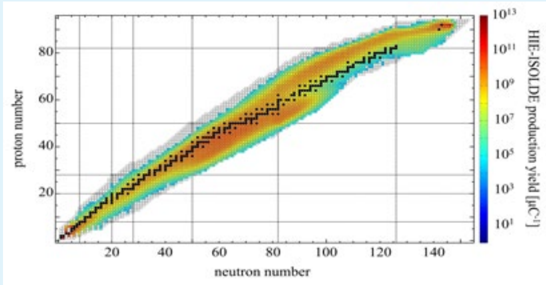


Illustration of the expected production yields per micro-Coulomb of 2.0 GeV protons on a UCx target

also the insertion of a pre-buncher to the RFQ accelerator at a subharmonic frequency, which would allow increased bunch spacing without a major transmission loss. There are also plans to add a beam chopper between the RFQ and the IHS to clean the background of satellite bunches. In this way the astrophysics programme at ISOLDE will be boosted.

In the near future we plan to install a compact heavy-ion low-energy ring in order to be able to perform experiments with stored, cooled secondary beams that can be used for studies spanning from nuclear ground-state properties to reactions studies of astrophysical relevance.

The intensity upgrade has two fronts. The first part is due to the increase of intensity of the proton beam by a factor of three and energy to 2 GeV and it is expected in 2021. This corresponds to an increase in power on target larger than a factor of three. The expected increase in production runs linearly with the increase in intensity. For the increase of production with energy we expect equivalent rates for fission and increase of factor 2-10 for spallation and fragmentation products. The other front corresponds to the active beam development programme continuously realised at ISOLDE aiming to improve the number of radioactive beams, their intensity as well as the isotopic and isobaric purity. A major upgrade of the laser ion source (RILIS) started in 2008. It has given new possibilities for radioactive beam production and drastically improved the intensity and purity of many beams. Building upon the ISOLDE Cooler and buncher experience a redesigned high resolution separator (HRS) incorporating an RFQ cooler has been studied with the aim to improve mass resolution from the present M/ΔM of 6000 to the originally designed value of 20.000 units. The system will be complemented with an isobar selection using a general purpose Multi-Reflection time-of-flight mass spectrometer. The diversity of beams and their quality will therefore increase significantly over the next few years.

SHE Factory, Dubna, Russia

Experiments on the synthesis of new superheavy elements using fusion reactions, because of the extremely small cross sections, require several months to obtain a single event. In the last decade, research on the synthesis of superheavy elements at JINR FLNR were conducted mainly using the ^{48}Ca ion beams. The intensity of an ion beam of ^{48}Ca in the U-400 cyclotron was brought to 1.2 pμA, which allowed to successfully synthesise new elements with Z = 113, 114, 115, 116, 117 and 118.

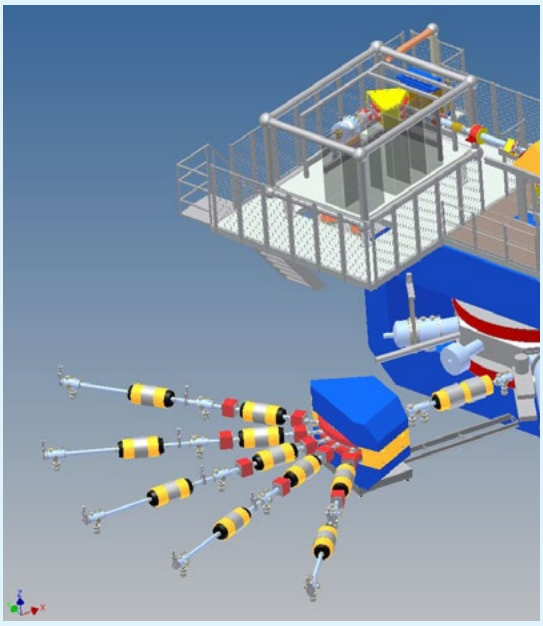
At present, the JINR FLNR implements the project of a Super Heavy Elements (SHE) Factory. The construction of the Superheavy Element Factory (SHE) plays a crucial role in the implementation of the research plans aimed at the study of the superheavy mass area. The Factory is based on the high-intensity universal DC280 cyclotron (A≤ 238, E ≤ 10 MeV/A , I ≤ 20 pμA) and will be constructed in a new separate experimental building. The new building is ready for installation of the DC-280 cyclotron, the commissioning and testing of the accelerator are ongoing, and the first experiments should begin in 2018.

The new accelerator will operate as a stand-alone machine. It is necessary to provide acceleration of ions from carbon to uranium up to the energy of 4–8 MeV/A with stepwise and smooth energy variation. For ions with masses A<70, the beam intensity should be not below $6{\cdot}10^{13}$ 1/s (10 pμA).

The synthesis of isotopes of element Z=115 in the ^{48}Ca+^{243}Am reactions was chosen as the first-day full-scale experiment. During this experiment, the performances of all the systems of the new accelerator and gas-filled separator (GFS-2) will be tested.

To get access to superheavy nuclides with Z>118 and carry out a detailed study on their properties, a sufficient increase in the beam intensity and the development of separators that provide the necessary background suppression are needed. This is the main goal of the construction of a first-ever SHE Factory. The 1000-m^2 experimental hall of the Factory is designed in compliance with class II radiation safety requirements for work with high-active targets made of transuranium isotopes.

To choose the separation principle analyses were made of the kinematic characteristics of different products for several hundred reactions leading to the formation of heavy nuclei. Unfortunately, the use of solely magnetic fields is inapplicable in case of fusion reactions. Thus, electrostatic separators (energy selectors), velocity filters, and gas-filled systems were considered. Further analysis showed that it is reasonable to construct three separators optimized for specific tasks.



Schematic layout of the DC-280 cyclotron for the SHE Factory, Dubna, Russia

A universal gas-filled separator will be used for the synthesis and study of the properties of heavy isotopes and the investigation of reaction mechanisms.

A velocity filter was chosen for a detailed spectroscopic study of heavy isotopes. This separator, named SHELS, is manufactured, equipped and installed for testing and in use at the beam of the U400 cyclotron.

To study the radiochemical properties of SHE, extremely high suppression factors are not needed. One needs to work with thick targets at high beam intensities. A gas-filled superconducting magnet was considered for this purpose.

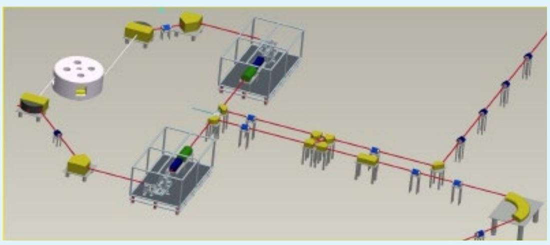
SPES, Legnaro, Italy

SPES is a new mid-term ISOL facility dedicated to the production of neutron-rich beams. It is an INFN project involving the two national laboratories, LNL and LNS and other INFN sites in Italy. SPES consists of a proton driver, a 70 MeV cyclotron with two exit ports for a total current of 750 μA, an UC_x ISOL target and ion source, a beam transport system with a high resolution mass selection and the superconductive PIAVE-ALPI accelerator complex in operation at LNL that will be used as radioactive beam re-accelerator.

A proton beam of 40 MeV and 200 μA, delivered by the cyclotron, will impinge on an uranium carbide target and neutron rich isotopes will be produced as fission fragments with a rate of 10^{13} fission/s. The uranium carbide targets have been fully developed and represent a technical innovation in terms of capability to sustain the primary beam power. The neutron rich products will be extracted in a 1^+ state with different ion sources and mass separated. The low energy selected beams will be transported to the linear accelerator ALPI. To fit the proper entrance parameters for beam re-acceleration with the linac, an RFQ-cooler and a charge breeder are needed. The charge breeder has been already constructed, in collaboration with SPIRAL2, and is under installation.

The re-acceleration stage with the superconductive linac ALPI qualifies the project in terms of good quality of beams (intensity and energy spread) and in the final energy interval (5-15 MeV/nucleon) which is ideal for nuclear reactions between medium-heavy mass ions close to the Coulomb barrier. With the high intensity beams delivered by SPES, a challenging and broad range of studies in nuclear spectroscopy and reaction mechanisms will be performed. Interesting areas where new data will be obtained are those concerning nuclear properties of the very neutron rich regions, where shell evolution is a question requiring an extensive experimental programme. The question on how the pairing interaction is modified in the nuclear medium will receive significant inputs by measurements of nucleon transfer reactions to specific nuclear states. Isospin effects in the collective rotation up to excitations in the order-chaos transition region and in the gamma-ray production due to the dynamical dipole emission, will be studied by varying up to extreme values the N/Z of the projectiles. Sub-barrier fusion with neutron rich ions will be studied, this process being a tool to investigate the tunnelling mechanism in presence of very positive Q-values, an issue interesting also for astrophysics.

The SPES project also has a part devoted to applied research and applications in conjunction with the possibility to use a second exit port of the cyclotron. Interest in this connection has been already declared. In particular, the high intensity proton beam could be used to produce neutrons in a wide energy spectrum, which, in turn, is interesting for measurements of neutron capture reactions of astrophysical interest. Plans to use the neutron flux for applications in the field



Schematic layout of the SPES facility at LNL, Legnaro, Italy

of chemistry, radiobiology, materials science and energetics are presently in the discussion phase.

The interdisciplinary project LARAMED funded by the Italian Ministry of University and Research will be devoted to the production of radioisotopes for therapy and diagnostics in medicine and other related applications.

PLANNED AND RELEVANT NEW FACILITIES

The European Spallation Source – ESS

The European Spallation Source (ESS) is under construction in Lund in Sweden (https://europeanspallationsource.se). 15 countries are currently founding members or observers of this European Research Infrastructure Consortium (ESS ERIC).

The ESS facility will be the first long-pulse neutron spallation source in the world. The neutron pulse length is 2.86 ms with a repetition rate of 14 Hz and determined by the proton pulse length and the 5 MW average power (125 MW peak power) design goal. A new flat moderator design pioneered at ESS will increase the brightness of the facility further.

22 instruments have been presented in the Technical Design Report and 15 neutron scattering instrument projects are already in construction. They will create new research opportunities in life sciences, energy, environmental technology, cultural heritage and fundamental physics. A cold neutron beam instrument for particle/nuclear physics is likely to be included in the next round of instruments approved for construction. The currently proposed instrument has been optimised for studies of neutron decay, hadronic parity violation, and delicate measurements of neutron electromagnetic properties with operational modes similar to existing facilities.

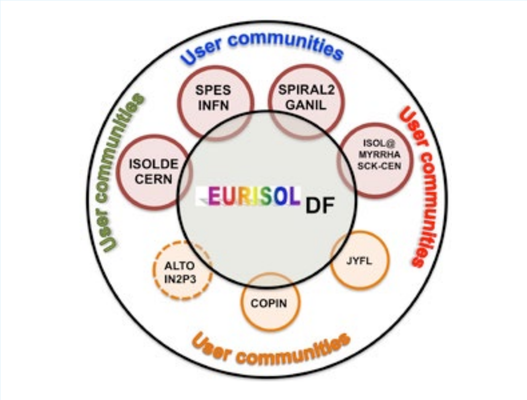
There is an expression of interest for a dedicated in-beam (super fluid Helium) ultra-cold neutron (UCN) source (https://arxiv.org/abs/1004.2716). UCN with energies around 100 neV are a unique tool due to their outstanding property to be storable and hence observable for long periods of time (several hundreds of seconds) to study fundamental properties of the free neutron, like its beta-decay lifetime, its electric dipole moment and its wave properties. The possibility to conduct a sensitive search for neutron-antineutron oscillations also represents a unique opportunity to address deep scientific questions in fundamental physics. The ESS baseline design includes a beam port that views a large area moderator and allows for the installation of a beamline that can accommodate a large acceptance expanding neutron guide with a neutron flight path of ≥ 200 m.

EURISOL Distributed Facility

The EURISOL project is, together with FAIR, one of the major aims of the Nuclear Physics community in Europe. In order to reach the long-term goal of EURISOL a new European strategy is proposed with an intermediate and ambitious step: EURISOL Distributed Facility (EURISOL-DF), http://www.eurisol.org/eurisol_df/).

The goals of EURISOL-DF are:

- implement a new scientific policy tackling major problems in nuclear physics at ISOL-based European facilities and in particular:
    - organise experimental campaigns using all available observables, techniques, facilities and theoretical approaches to answer key questions in nuclear structure (eg. modifications of magic numbers in nuclei far from stability) and astrophysics (eg. genesis of middle to heavy mass elements in the Universe) ;
    - have a single entry point for a significant fraction (up to 50%) of the Radioactive Ion beamtime dedicated at ISOLDE-CERN, SPIRAL2-GANIL & SPES-INFN for the EURISOL-DF experiments and distributed via the EURISOL-DF Programme Advisory Committee;
- develop R&D on RIB production and instrumentation towards EURISOL and in particular:
    - organise and open to all EURISOL-DF members the R&D platforms to develop RIB (ex. ion sources test benches, target developments, separation techniques) and detector systems;
- promote user driven policy with an important role played by the EURISOL User Group and the EURISOL Instrumentation Coordination Committee in order to organise and optimise the campaigns of travelling detectors and arrays;
- have EURISOL-DF included in the ESFRI list and attract additional member states and EU funds, in particular:
    - in-kind and/or cash contributions of the members for joint developments for EURISOL in the domains of accelerators, RIB production and instrumentation for experiments;
- establish a joint strategy in education and training in nuclear science (eg. organising joint summer schools, hands on training, topical workshops and conferences);



Schematic illustration of the concept for the EURISOL-DF initiative displaying the members and user communities.

- develop EURISOL as a single site facility as a long-term goal.

The EURISOL-DF membership will be open to all European RIB ISOL facilities. The core facilities of the new distributed infrastructure will be GANIL-SPIRAL2, CERN-ISOLDE, INFN-SPES and ISOL@ MYRRHA as a candidate for the future core member. The JYFL, COPIN and ALTO will be the associated members of the EURISOL-DF consortium.

EURISOL-DF will closely collaborate with the FAIR facility and other ISOL facilities worldwide and it will strongly interact with the EURISOL Joint Research Activity in the Horizon 2020 ENSAR 2.

The EURISOL-DF initiative is coordinated by the EURISOL Steering Committee representing partners who signed the EURISOL Memorandum of Understanding, namely GANIL (France), CERN/ ISOLDE, COPIN (Poland), SCK-CEN for Belgian EURISOL Consortium (BEC), INFN (Italy) and JYFL (Finland).

Map displaying the core members of EURISOL-DF, CERN-ISOLDE, INFN-SPES, SPIRAL2 and ISOL@MYRRHA (at a later stage), and the associeted members JYFL, COPIN and ALTO.

IFMIF-DONES

IFMIF - the International Fusion Materials Irradiation Facility in its current version IFMIF-DONES (DEMO - Oriented Neutron Source) – is a dedicated neutron source facility for studies of materials, which is planned as part of the European fusion energy programme. Its main goal will be to study properties of materials under strong irradiation by fast neutrons. It is a key facility to prepare for the construction of the DEMO Demonstration Power Plant envisaged to follow ITER.

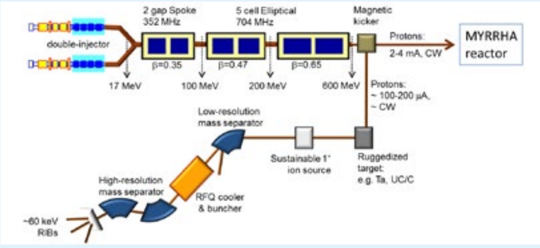
Several European countries have declared interest to host the IFMIF facility. One of the possible host countries, Poland, came with a very interesting idea to extend the objectives of the IFMIF facility beyond its standard programme of material studies for thermonuclear fusion reactors. Various scientific areas, such as astrophysics, medicine, nuclear physics and new technologies are under consideration to be realized simultaneously with the standard operation of the IFMIF facility.

MYRRHA, Mol, Belgium

From 1998 on, SCK•CEN is designing the MYRRHA facility, Multipurpose hYbrid Research Reactor for High-tech Application, based on the coupling of a proton accelerator, a liquid Lead-Bismuth Eutectic (LBE) spallation target and a LBE cooled, sub-critical fast core. The MYRRHA project, aims at constructing an Accelerator Driven System (ADS) as a pan-European research infrastructure at the SCK•CEN site in Mol (Belgium).

Presently, MYRRHA is conceived as a flexible fast spectrum irradiation facility, able to operate in an ADS subcritical mode or as a critical reactor. Besides demonstrating the full ADS concept for the study of efficient transmutation of high-level nuclear waste, MYRRHA will allow nuclear fuel R&D for innovative reactors, structural-material development for GEN IV and fusion reactors, radioisotope production for medical and industrial applications.

The MYRRHA design is considering that up to 5% of the proton beam provided by the MYRRHA accelerator (proton energy of 600 MeV and a maximum beam intensity of 4 mA in CW mode) will be used to feed an Isotope Separator On-Line facility: ISOL@MYRRHA. This facility will receive up to 200 μA 600 MeV protons and will use a range of target materials (carbides, metal foils, powders) for production of a large variety of radioactive ion beams. High purity will be reached by the installation of a high-resolution mass separator preceded by a pre-separator and an RFQ cooler and buncher.



Schematic layout of the MYRRHA facilities including ISOL@MYRRHA, Mol, Belgium

ISOL@MYRRHA will provide intense low-energy Radioactive Ion Beams (RIB) for experiments requiring very long beam times (up to several months). This will open unique opportunities for RIB research in various scientific fields, ranging from fundamental-interaction measurements with extremely high precision over systematic measurements for condensed-matter physics and the production of medical radioisotopes. Experiments, requiring very high statistics, needing many time-consuming systematic measurements, hunting for very rare events, and/or having inherent limited detection efficiency, have a particular interest in the use of extended beam time. This makes ISOL@MYRRHA complementary with the activities at other existing and future facilities. During the main shut-down maintenance periods of the MYRRHA reactor (3 months every 11 months), the full proton beam intensity can be used for ISOL@MYRRHA or other applications.

In 2013, seven Belgian universities and research institutes formed the Belgian EURISOL Consortium (BEC) joining their efforts in a coordinated action of ISOL developments in Belgium and supporting ISOL@MYRRHA and the developments towards the EURISOL Distributed Facilities.

In 2014, the Belgian federal government, in its coalition agreement, has foreseen a gradual financial support to pursue the realisation of MYRRHA project as an international project aiming to develop innovative solutions for high level radioactive waste, materials research on fusion reactors, fundamental nuclear research and also for retaining the production of medical radio-isotopes in Belgium.

In 2015, after an in-depth evaluation of the MYRRHA project with involvement of international evaluation committees a new implementation plan has been adopted. The MYRRHA project will be realised in a phased approach. In a first phase, the linear accelerator until 100 MeV and three target stations of which one is of the type ISOL will be constructed. This ISOL smaller-scale facility will evolve towards the ISOL@MYRRHA facility after the second phase of the MYRRHA project, i.e. the construction of the proton accelerator up to 600 MeV. The intention is to allow retrofitting the 100-MeV facility to use 600-MeV protons foreseen in the phase 2 of the MYRRHA project. The third phase of the project consists of the realisation of the sub-critical reactor.

The 100-MeV accelerator including the target stations is foreseen to be commissioned by 2022 and fully operational by 2024. The detailed planning of the phase 1 is under preparation for final decision by the end of 2017.

SMALL-SCALE ACCELERATOR FACILITIES

For more than four decades, small-scale national or university-based low-energy stable-beam and electron facilities have decisively contributed to our understanding of nuclear structure as well as of stellar evolution and nucleosynthesis. In addition, they developed a variety of powerful analytical techniques aiming at the study of problems with societal impact, notably cultural heritage problems, environmental pollution and monitoring, human health issues, characterization of advanced materials for future energy applications etc.

Small-scale accelerator facilities play a crucial role in providing expertise in experimental techniques and equipment development that, in most cases, support the large-scale facilities. On top of these, small-scale facilities contribute decisively in preserving the essential knowledge in the field of nuclear science and maintaining the essential skills and capabilities, particularly through education and training of a new generation of nuclear physicists.

The main features of 17 of such facilities are given in the table given below.

Map indicating schematically the location of the facilities described in the table below

Small scale accelerator facilities across Europe	
NCSR "Demokritos", Athens, Greece	5 MV Tandem accelerator: 6 beam lines; DC ion-beams from Z=1 (protons) to Z_50 (tin); Secondary mono-energetic neutron beams from thermal to 0.5 MeV, 5-11 MeV and 16-18 MeV; 250 keV high-current p/d single-stage accelerator PAPAP: one beamleg.
CENBG. Bordeux-Gradignan, France	AIFIRA: Inline 3.5 MV Singletron (HVEE) accelerator that delivers H+, D+ and He++ DC beams with intensity up to 50 μA. Monoener-getic neutrons are produced in the range 100 keV – 7 MeV. Five beamlines are avaible for material characteri-zation, high resolution imaging, irradiation and neutron production
Caserta, Center for Isotopic Research on Cultural and Environmental Heritage, Italy	3MV Tandem-Pelletron accelera-ting H to U up to about 20 MeV, including a radio chemistry lab for ^{7}Be beam production and radioisotopes handling. 2 Mass spectrometers for stable isotopes.
Darmstadt S-DALINAC, Germany	The S-DALINAC is a recirculating superconducting electron linac operating at 3GHz. The accelerator delivers cw-beam to various experimental setups with energies from 3 to 130 MeV.
Atomki Inst. for Nuclear Research, Hungarian Academy of Sciences, Debrecen, Hungary	Atomki Accelerator Centre: Cyclotron (1-26 MeV), VDG-5 Van de Graaff generator (0.8-3.8 MeV), VDG-1 Van de Graaff generator (90-1500 keV), ECR ion source (50 eV-800 keV), AMS accelerator mass spectrometer for radiocarbon dating (200 keV)
Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Germany	Tandetron Electrostatic Accelera-tor 6 MV with universal ion source High-current Tandetron Electro-static Accelerator 3 MV with uni-versal ion source Single stage van-de-Graaff accelerator 1.7 MV for light gaseous ions 3 ion implanters with universal ion sources 500 kV, 200 kV, 40 kV.
SUERC, East Kilbride, United Kingdom	5MV tandem and 250kV single stage accelerators for AMS of ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{40}Ca and ^{129}I. 2 preparation laboratories for ^{14}C, 2 preparation laboratories for ^{10}Be, ^{26}Al and dedicated preparation laboratory for ^{36}Cl. Mineral separation and chemical analysis facilities (ICP-MS and ICP-OES) to support cosmogenic isotope analysis
LABEC Accelerator Laboratory, Firenze, Italy	Tandetron accelerator, 3 MV, mainly for Ion Beam Analysis using external beams and micro-beams, and C-14 measurements with Accelerator Mass Spectro-metry. Also available elemental analysis systems (XRF, in-lab and transportable)
MLL: Maier-Leibnitz Laboratorium, Garching, Germany	15 MV MP tandem producing H to U including polarised p and d, DC or bunches of 1 ns to 2 ms with frequencies of 5 MHz.
Institut für Kernphysik, Universität zu Köln, Germany	10 MV FN Tandem accelerator producing light and heavy ion (Z up to 30) beams with energies up to 120 MeV. The beam can be pulsed to bunches of 2.5 ns with frequencies up to 2.5 MHz. Typical beam currents are 10-100nA. 6MV Tandetron for AMS of all cosmogenic nuclides.
Laboratory of Accelerators and X-Rays diffraction, IST- Universidade de Lisboa, Portugal	2.5 MV Van de Graaff accelerator: 3 experimental lines for IBA techniques with proton and alpha beams and a microprobe with external beam; 3 MV tandem accelerator, equipped with an accelerator mass spectroscopy (AMS) system with a lateral resolution of 30 µm and 2 beam lines for IBA and 1 beam line for nuclear physics.
CMAM: Centro MicroAnalisis de Materiales Univ. Autonoma de Madrid, Spain	5 MV Tandem accelerator, coaxial Cockcroft-Walton type; Two ion sources: HVEE 358 Duoplasma-tron and HVEE 860

Oslo Cyclotron Laboratory, Univ. of Oslo, Norway	Scanditronix MC-35 Cyclotron for light ions: protons (max. 35 MeV), deuterons (max 18 MeV), ^{3}He (max 47 MeV) and ^{4}He (max 35 MeV).
Nuclear Physics Institute ASCR, Rez near Prague, Czech Republic	Cyclotron U-120M: Isochronous cyclotron (K=40) for light ions operated in both positive (p, D, $^{3}He^{2}$, $^{4}He^{2+}$) and negative (H^{-}, D^{-}) modes. Tandetron 4130 MC: 3MV Tandem accelerator producing a wide range of ions up to Au. Mostly H+ and He+ beams.
CAN: Centro Nacional de Aceleradores, Sevilla, Spain	3MV Tandem accelerator: Ion Beam Analysis (IBA) for material characterization and modification; 1MV Tandetron accelerator: mass spectrometry of ^{129}I, ^{239}Pu, ^{240}Pu, ^{41}Ca, ^{36}Cl, ^{26}Al, ^{10}Be and ^{236}U; 18/9 MeV Cyclotron for PET radionuclide (^{11}C, ^{13}N, ^{15}O, ^{18}F) production and studies of effects of proton irradiation
VERA: Vienna Environmental Research Accelerator, Vienna Univ., Austria	3 MV Tandem accelerator mainly used for Accelerator Mass Spectrometry (AMS) up to Pu. Two Multi-Cathode Sputtering Sources for negative ions.
RBI: Rudjer Boskovic Institute, Zagreb, Croatia	6.0 MV EN Tandem with two ion sources (Alphatros for He and SNICS 40 for other ions); 1.0 MV Tandetron with duoplasmatron ion source; 8 beam lines including heavy ion microprobe and dual beam irradiation chamber

1

HADRON PHYSICS

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1. HADRON PHYSICS

INTRODUCTION

Among the most challenging and fascinating goals of modern physics are the endeavours to understand how the spectrum and structure of hadrons emerge from the forces among their fundamental constituents and to find out whether there are new forms of matter. This requires a fully quantitative understanding of the strong interaction, especially in the non-perturbative (i.e. low-energy) regime, which is the subject of hadron physics. The modern theory of strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non-Abelian gauge group SU(3). It is one of the pillars of the Standard Model (SM) of particle physics. While QCD is well tested at high energies, where the strong coupling constant α_s is sufficiently small for perturbation theory to apply, it becomes a strongly coupled theory in the low energy regime where many aspects await a better understanding. Significant progress has been made over the past few years thanks to considerable advances in experiment and theory. New experimental results have stimulated intense theoretical activity and a refinement of the theoretical tools. In spite of these developments, many fundamental questions concerning the structure and spectroscopy of hadrons remain unanswered. Furthermore, key issues such as the confinement of quarks or the existence of glueballs and hybrids are long-standing puzzles and present an intellectual challenge in our attempt to understand the nature of the strong interaction and of hadronic matter.

The theoretical description of the strong interaction has given rise to some of the most influential ideas in quantum field theory. QCD has been instrumental for establishing the Standard Model and provides accurate descriptions of many experimental observations. The importance of QCD can be highlighted by the fundamental role it plays in many apparently unrelated fields. First and foremost it gives rise to the mass of visible matter in the universe. QCD contains eight out of 19 parameters of the SM (the strong coupling, the six quark masses and the strong CP-violating parameter) and plays a central role in the determination of another four SM parameters, i.e. the parameters of the quark mixing matrix. QCD is essential for investigations at the energy frontier (since it describes the SM background to non-SM physics) as well as at the intensity frontier (since in the low-energy regime QCD is often the limiting factor in indirect searches for physics beyond the SM). Finally the QCD phase diagram plays a crucial role in cosmology and astrophysics.

Experiments that test QCD use various probes to investigate different aspects of hadron spectroscopy, hadron structure and hadron dynamics. These experiments explore both the non-perturbative and perturbative regimes. High-momentum processes, such as Deep Inelastic Scattering probe the perturbative regime, in which the observables are directly related to the quark and gluon degrees of freedom of the QCD Lagrangian. In these processes the soft (non-perturbative) part of the amplitude gives access to key aspects of hadron structure, such as the spatial distribution of quarks in the proton, or the connection between the quark spin and orbital angular momentum and the spin of the proton.

On the other hand, low-momentum processes explore QCD in the non-perturbative regime. These processes have largely resisted a treatment in terms of the quarks and gluons of the QCD lagrangian. Theoretical calculations can be carried out by means of computer simulations on a discretised space-time lattice (Lattice QCD) or using effective field theories based on hadronic degrees of freedom that respect the symmetries of QCD. Other possible theoretical approaches to non-perturbative QCD are functional methods as well as phenomenological models. A significant amount of additional experimental data is required to identify the relevant degrees of freedom. This is one of the main goals of hadron spectroscopy.

Understanding the physics of hadrons requires a large variety of complementary experiments and theoretical tools. In experiments, electromagnetic and hadronic probes can be used to study various aspects of hadron structure, spectroscopy and dynamics at different energy scales. These different experimental techniques provide complementary information, and it is of vital importance that all be pursued in order to obtain a complete picture and reach a full understanding of the field. In this respect a central role will be played by the antiproton programme at the FAIR facility under construction in Germany. FAIR is expected to produce groundbreaking results in all fields of nuclear physics and will, in particular, provide a unique research environment for all aspects of hadron physics coming from experiments with antiprotons. Tremendous theoretical progress has been achieved by lattice QCD and effective field theories, leading to *ab-initio* calculations of many hadronic properties. Of fundamental importance to the progress in hadron physics is the interplay between theory and experiment, which must continue in the future.

This chapter is organised as follows: after an introduction to the basic properties of QCD and the most important theoretical and experimental techniques, the three areas of hadron physics (spectroscopy, structure, dynamics) will be reviewed, highlighting, for each field, the state of the art and future perspective. The particular role of lattice QCD will be described before we formulate our recommendations for the future development of the field of hadron physics.

THEORETICAL FRAMEWORK

The challenge for theoretical hadron physics is to obtain a quantitative description of the properties and the dynamics of hadrons in the low-energy regime. QCD is a non-Abelian gauge theory that describes the strongly interacting sector of the Standard Model in terms of the fundamental constituents of hadronic and nuclear matter, i.e. the quarks and gluons. Quarks are massive spin–1/2 matter fields. They carry fractional electric charges and come in six "flavours", while the interactions are mediated by eight massless gauge bosons, the gluons. Quarks and gluons are also charged under the gauge group $SU(3)_{colour}$. The strength of the interaction is determined by the dimensionless parameter, α_s, called the strong coupling constant. As in any quantum field theory, this coupling depends on an energy scale. At the quantum level, QCD generates a fundamental dimensionful scale Λ_{QCD}, which controls the variation of α_s with energy. Unlike electromagnetism one finds that α_s decreases with increasing energy. This property is called asymptotic freedom, which has been spectacularly confirmed, for example, by the kinematic variation of cross-section measurements in high-precision deep-inelastic electron-proton scattering. Asymptotic freedom ensures that processes involving the strong interaction at high energies can be computed reliably in perturbation theory in α_s. However, by the same token one finds that α_s becomes large at low energies, i.e. in the region relevant for hadron physics. Since the dynamics of quarks and gluons is strongly coupled in this regime one has to resort to non-perturbative techniques, such as Lattice QCD, effective field theories (EFTs) and functional methods based on Dyson-Schwinger and functional renormalisation group (FRG) equations. More details on these formalisms can be found in the "boxes".

Another unique feature of QCD is confinement, i.e. the fact that quarks and gluons are not observed as free particles but only occur as bound constituents within hadrons. The quarks and gluons, which form the fundamental degrees of freedom of QCD reveal themselves only at large energies but remain hidden inside hadrons in the low-energy regime. In mathematical terms this means that the only strongly interacting particles observed in nature are "colourless" and transform as singlets under the gauge group $SU(3)_{colour}$. While there is overwhelming experimental evidence for confinement, the theoretical understanding of this phenomenon continues to be an active field of research. In pure gluodynamics, i.e. in the absence of quarks, lattice QCD calculations of the static quark-antiquark potential display a linearly rising behaviour when the separation between quark and antiquark is increased, which implies that an infinite amount of energy is required to isolate free colour charges. This effect cannot be explained in perturbation theory. In the presence of dynamical quarks the linear rise of the potential is eventually stopped, due to hadronisation, the detailed nature of which is studied in connection with heavy ion collisions and is also of great importance for the design of event generators in collider physics.

The description of the strong interaction in terms of the non-Abelian gauge theory of QCD has important consequences for the observed hadron spectrum. In particular, QCD permits the existence of states that cannot be accommodated in the simple quark model, such as glueballs, which are composed of gluonic degrees of freedom only. While the formal mathematical proof for the existence of a state with non-vanishing mass in pure gluodynamics is one of the still unsolved Millenium Problems, the spectrum of glueballs has been determined in lattice QCD. Reliable predictions for glueball masses are, however, difficult to obtain, due to the complicated mixing patterns with mesons.

Quark masses vary over more than three orders of magnitude. The light quarks (up, down) have masses at the level of a few MeV, with the strange quark being somewhat heavier. Therefore, these quarks can be considered nearly massless at typical hadronic scales. As a consequence, QCD possesses a chiral symmetry which becomes exact when all quark masses are taken to vanish. One finds that chiral symmetry is spontaneously broken due to the formation of a chiral condensate,

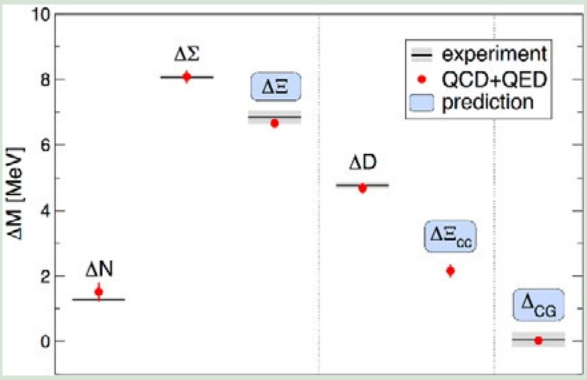
Box 1: Lattice Methods for Nuclear Science - A Grand Challenge for Computational Science

Numerical simulations of Quantum Chromodynamics formulated on a discrete space-time lattice have become an essential tool in strong interaction physics. Lattice QCD aims at providing quantitative information on nuclear and hadronic properties in terms of the fundamental constituents of matter and their interactions.

Baryonic mass splittings computed in Lattice QCD by the BMW collaboration. *ΔN* denotes the proton neutron mass difference including electromagnetic effects.

Thanks to the significant increase in the capabilities of large-scale supercomputers in conjunction with the enormous progress made in developing efficient simulation algorithms, calculations can now be performed at the physical value of the pion mass on a routine basis. The overall accuracy has even been pushed to a level at which it is possible to resolve isospin-breaking effects induced by electromagnetism, as well as the mass splittings between the up and down quarks. These recent refinements have, for instance, allowed for an accurate determination of the mass difference between proton and neutron from first principles. Lattice QCD is also an essential ingredient for the interpretation of experimental data collected in heavy-ion collisions, in order to explore the phase diagram of strongly interacting matter. Furthermore, lattice methods are applied to study properties of nuclear matter. Here the numerical simulation of effective theories for light nuclei has proved very successful and enabled, for instance, the *ab initio* study of the scattering of alpha particles.

These examples show that numerical simulations of theories describing strongly interacting systems have become an indispensable tool for a great variety of problems in nuclear science. Further progress in this field relies not only on further theoretical and algorithmic developments but also on the availability of sufficient computer power. At the dawn of the era of Exascale computing, nuclear science has an important strategic role in supporting European leadership in computing.



as is apparent from the observation of an octet of light pseudoscalar mesons in accordance with Goldstone's theorem. In the opposite limit of infinitely heavy quarks QCD has an exact spin-flavour symmetry. The charm and bottom quarks have masses in excess of 1 GeV, which is well above the intrinsic energy scale Λ_{QCD}. Indeed one finds that hadrons containing these quark flavours exhibit many of the features implied by the spin-flavour symmetry, such as the suppression of fine and hyperfine mass splittings.

The symmetries of QCD are not only important for the interpretation of the hadron spectrum but also form the basis for so-called effective field theories (EFTs). Chiral Perturbation Theory (ChPT) allows for the treatment of processes involving the up, down and strange quarks in terms of hadron fields, which are the relevant degrees of freedom at low energy scales. Spin-flavour symmetry is the basis for the Heavy Quark Effective Theory (HQET), which leads to a simplified description of the spectrum and decays of hadrons containing one or several of the charm or bottom quarks.

QCD is the prototype of a strongly coupled theory – the only one realised in experimental data up to now – and inspires new theoretical descriptions for strongly interacting systems with many possibilities for cross-fertilisation with fields like condensed-matter physics. The theory toolkit to study hadrons from QCD is quite diverse, as befits the rich set of phenomena it describes. It includes semi-classical gauge theory, functional methods and Schwinger-Dyson equations, techniques using limits in large number of colours, as well as tools derived from string theory. In addition, models at different levels of sophistication allow for new ideas that describe the structure and dynamics of hadrons to be confronted with experimental data.

During the past decade there has been enormous progress in applying QCD in the low-energy regime, thanks to advances in lattice QCD, effective field theories and functional methods. Moreover, data-driven approaches based on dispersion theory and phenomenological models continue to play an important role.

Box 2: Effective Field Theories

Effective field theories (EFTs) are a standard method for analysing physical systems with different energy scales. Crucial for the construction of an EFT is the notion of factorisation, whereby the effects in a physical system can be separated into short-distance and long-distance (low-energy) contributions, with each factor amenable to calculation by different techniques. The short-distance factor is typically calculated using analytic techniques, such as weak-coupling perturbation theory and the renormalisation group, while the low-energy contribution may be determined in lattice QCD or phenomenological methods. Low-energy EFTs such as Chiral Perturbation Theory retain as dynamical variables the relevant hadronic degrees of freedom, while the short-distance contribution is absorbed into effective coupling constants. The underlying scale separation is largely based on symmetries that emerge from QCD in some limit.

The approximate chiral symmetry among the up, down and strange quarks forms the basis for Chiral Perturbation Theory (ChPT) which is formulated in terms of the Goldstone boson fields describing the pions, kaons and η-mesons. ChPT is instrumental for our understanding of many of the properties of light mesons and baryons, in studies of pion and kaon interactions and in the construction of nuclear forces from QCD. It also plays an important role in lattice QCD calculations, by providing theoretical constraints for the chiral extrapolation to the physical pion mass.

The properties of hadrons that contain heavy quarks (charm and bottom) whose masses are bigger than Λ_{QCD} depend only weakly on the spin and the flavour of the heavy quarks. This approximate spin-flavour symmetry forms the basis for the Heavy Quark Effective Theory, which has been instrumental for studying the properties of D and B mesons. For hadrons containing two or more heavy quarks additional symmetries allow for the construction of other EFTs such as potential non-relativistic QCD. In this way a QCD-derived description of the properties of heavy quarkonia and of baryons with two heavy quarks could be achieved, which is important for our understanding of the X, Y and Z resonances discovered in the charm sector.

Thus, a range of calculational tools is available with complementary strengths and weaknesses. Considering the wealth of precise experimental data that can be analysed using this variety of theoretical methods, one can rightly claim that hadron physics is entering the precision era. During the coming decade one can therefore expect significant progress in many areas, including accurate determinations of hadronic uncertainties in precision observables (such as hadronic contributions to the muon anomaly), calculations of nucleon form factors relevant for the determination of the proton radius and other structural properties, as well as the interpretation of the spectrum of heavy quarkonia and hadronic states in the charm sector.

EXPERIMENTAL METHODS

In order to answer the open questions in hadron physics, dedicated experiments that test QCD in the non-perturbative regime are crucial to improve our limited understanding of these aspects of QCD. These measurements include the study of QCD bound states, the search of new forms of hadronic matter (hadron spectroscopy) and the study of hadron structure and of hadron dynamics. These investigations can be performed with different probes such as electrons, photons, pions, kaons, protons or antiprotons.

Many complementary approaches contribute to the knowledge of hadronic structure and dynamics. Historically lepto-production of hadrons has been the main tool to study the internal structure of the nucleon and its modification in nuclear matter as the probe interacts electromagnetically. It covers a large range of photon virtualities starting from real photons, allowing for elastic, inclusive, semi-inclusive and exclusive reactions with which one can access form factors, parton distributions up to transverse momentum distributions (TMDs) and generalised parton distributions (GPDs) which encode the information describing the 3D-structure of the nucleon. A complementary path for accessing TMDs is offered by Drell-Yan reactions in meson-nucleon, proton-proton (*pp*) and $\bar{p}p$ processes. An important characteristic of both lepto-production and Drell-Yan is the proven factorisation of the cross-sections into soft, non-perturbative terms and the hard process, while proton-proton collisions have the advantage of large cross sections, which is important for our ability to probe the gluon content of the nucleon.

For the field of hadron spectroscopy the main environments in which these studies have been carried out are e^+e^- and $\bar{p}p$ annihilation, pion-nucleon scattering, as well as photo- and electro-production.

In e^+e^- annihilation direct formation proceeds through an intermediate virtual photon and is therefore limited to the vector states ($J^{PC}=1^{--}$). Other production mechanisms include photon-photon fusion, initial state radiation (ISR) and B-meson decay. e^+e^- annihilation is characterised by the low hadronic background and the high discovery potential. The main disadvantage is that, as mentioned earlier, direct formation is limited to vector states and this implies a limited mass and width resolution for all other states.

In $\bar{p}p$ annihilation it is possible to form directly states with any (non-exotic) quantum number combination, via intermediate states with the appropriate number of gluons. For all these states the mass and width resolution is excellent. States with exotic quantum numbers can be reached in production mode. $\bar{p}p$ is a gluon-rich environment, particularly favourable for the discovery of hybrids and glueballs. All three pillars of hadron physics (spectroscopy, structure, dynamics) can be studied in $\bar{p}p$, provided that a universal detector is employed. The main disadvantage of $\bar{p}p$ is the high hadronic background. However previous experiments at CERN and Fermilab have shown that the selection of exclusive final states allows to reduce backgrounds significantly.

With photon beams, hadronic excitations can be readily identified via their decay products, since the initial (QED) interaction is well understood. Electroproduction allows for the study of transition form factors. The ability to polarise photon and electron beams as well as the respective targets opens up the possibility of measuring observables that can help distinguish between overlapping resonances through amplitude analyses. As with $\bar{p}p$ annihilation, electromagnetic probes can be used to investigate all three pillars of hadron physics.

HADRON SPECTROSCOPY

In any physical system, the manner in which it is excited is a fundamental manifestation of the underlying mechanisms that govern its behaviour. For instance, precise details of atomic spectra were instrumental in being able to deduce the properties of the electromagnetic interaction through the development of Quantum Electrodynamics (QED). Similarly, hadron spectra beautifully encode the complex properties of the theory of fundamental interactions: Quantum Chromodynamics (QCD).

The key idea in QCD is that hadronic states are colour-neutral, and this leads to the concept of mesons as bound quark-antiquark pairs, whilst baryons are systems that contain three quarks. “Exotic” hadrons can be loosely defined as states that are not explained in terms of these configurations, but that nonetheless retain the colour-neutrality demanded by QCD. Possible exotic configurations include multiquark states (e.g. tetraquarks, pentaquarks) and gluonic hadrons (hybrids and glueballs) in which excited gluons act as hadron components and determine their quantum numbers.

Hadron spectroscopy is the study of the meson and baryon spectrum (including the pattern of decays and transitions between states) and the search for exotics. Mesons are the simplest quark bound systems and are the ideal place to study quark-quark interaction. Baryons have a special role in spectroscopy since not only they are the building blocks of ordinary matter, but also because their three-quark structure is most obviously related to colour degrees of freedom. Exotic states, with quark configurations other than three quarks or quark-antiquark, can reveal new or hidden aspects of the dynamics of the strong interaction.

Why is hadron spectroscopy a prime tool to study the details of the underlying QCD interaction? At large momenta, the QCD coupling strength is weak and the interactions between quarks and gluons as well as the gluon self-interactions are precisely known. In bound states and resonances, however, the interactions occur at low momenta, where the QCD coupling becomes strong. As a consequence, the forces between the elementary particles become much more complicated to describe. They give rise to fascinating effects like dynamical mass generation, which accounts for 99% of the hadron mass and therefore of the visible mass in the universe. They also give rise to the intricate pattern of the spectra of mesons, baryons and the newly discovered exotic states. Extensive and precise spectroscopy, particularly of exotic states, combined with a thorough theoretical analysis of the data, will add substantially to our knowledge of the underlying strong interaction.

Recent Achievements and Hot Topics

There is more to spectroscopy than just bump hunting. In fact we need to understand the details of line shapes and information at the amplitude level in order to be able to study the nature of these states and their dynamics related to the underlying QCD forces. This involves experiments that require some combination of beam, target or recoil polarisation, which are technically very challenging.

In the energy region of the heavy quark sector (charm and bottom quarks) a plethora of new states has been discovered recently (Figure 1). Experimentally, this energy region is easier to deal with than the light quark sector since many of the observed states are narrow. Furthermore, the energy scale provided by the heavy quark mass facilitates the theoretical treatment of heavy quark systems in terms of effective field theories. As a consequence, exotic states are easier to identify. In particular the *X*, *Y* and *Z* states in the charmonium sector have shown strong evidence for novel configurations. However, more work is required to understand what sort of resonances they really are. Interestingly, these new states have shown up in experiments that were designed to perform precision measurements on conventional hadrons.

In the light quark sector (up, down and strange quarks), some of the most intriguing states are scalar mesons. In the ground state multiplet, there is still speculation about whether the f_0 and a_0 are regular meson states, tetraquarks or hadronic molecules. For higher masses, more f_0 states have been observed than can be accommodated in a quark model multiplet, leading to discussions about whether some of these states might be glueballs (see below). COMPASS has also observed a new meson, the a_1(1420), but its interpretation is still unclear. The study of these states is extremely complicated because of the large widths that make them difficult to identify against a large background. Therefore, it is crucial that investigations with different probes and via different decay modes be carried out.

Another critical and poorly studied sector is

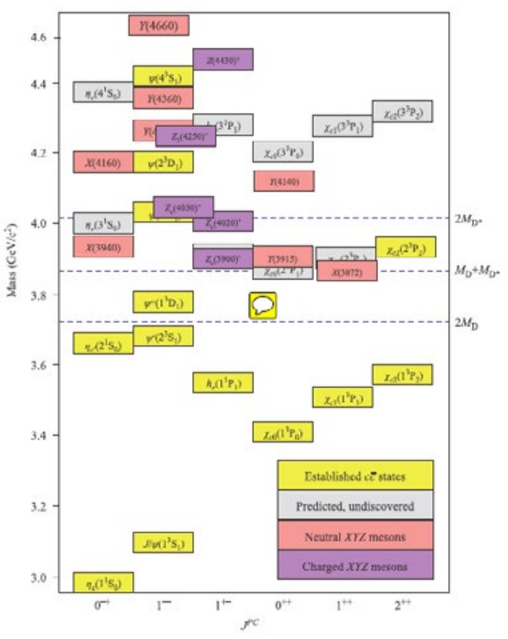


Figure 1: The spectrum of the *X*, *Y* and *Z* states.

strangeonium and strange-rich states; here the number of experimentally determined states is much smaller than expected, mostly because of limitations in the statistics and detector capabilities of previous experiments. Current and future experiments present a real opportunity for a dramatic improvement in our knowledge of the spectrum.

Evidence for the observation of states with explicitly exotic quantum numbers, for instance the π_1(1400) and π_1(1600), has been reported by several experiments. However, even after many years definitive conclusions have still to be reached.

The light quark sector is definitely more complicated than that of heavy quarks, but an understanding of light quark systems is an absolute necessity to claim that we understand hadrons. In the past, theoretical predictions were limited and quite model dependent but in the last decade, lattice QCD has made incredible progress in giving robust predictions for the light meson spectrum. Recent calculations reproduce the main features of the meson spectrum and provide indications for multiplets with exotic quantum numbers.

The self-interacting nature of gluons remains one of the most fascinating predictions of QCD. A direct observation of glueball states – states made prominently of gluons – will be the ultimate check of this prediction. While lattice simulations can make clear predictions for the glueball spectrum in the pure gauge theory without quarks, the mixing of states in the presence of light quarks is a challenge.

For several decades our knowledge of the light, non-strange baryon excitation spectrum stemmed essentially from data on elastic pion-nucleon scattering. Initially, the observed spectrum contained far fewer states than expected from the quark model or lattice calculations. A dramatic improvement occurred after performing partial wave analyses of new high-precision photoproduction data from MAMI, ELSA and JLab, including polarisation degrees of freedom. This has lead to the discovery of several new states while other previously discovered states have been established more firmly. This is illustrated by Table 1, which lists the entries of several baryon states in the Review of Particle Properties (RPP) in 2010 and 2016 along with their star ratings assigned by the Particle Data Group.

In addition, our understanding of the properties of the observed states has greatly improved in the light of the new data. In the future, new data – for instance from double-polarised photo-production off protons and neutrons,

	RPP 2010	RPP 2016
$N(1860)5/2^+$		**
$N(1875)3/2^-$		***
$N(1880)1/2^+$		**
$N(1895)1/2^-$		**
$N(1900)3/2^+$	**	***
$N(2060)5/2^-$		**
$N(2120)3/2^-$		**
$\Delta(1940)3/2^-$	*	**

Table 1

electro-production or ψ-decays – will provide a better understanding of the spectrum. Baryon spectroscopy would also benefit from new precise data from pion-induced processes. While the HADES experiment has already started to use the GSI pion beam, future projects involving meson beams are pursued at J-PARC. Pion production of baryonic resonances can be studied at HADES via the measurement of two-pion and dilepton final states, which provides a complementary perspective on baryonic resonances compared to photo- and electro-production. On the basis of the new data one hopes to answer questions such as: Why are certain baryon multiplets completely empty? Are specific sets of quantum numbers indeed not realised as observable states in nature? And if this is the case: Why?

New data obtained from existing (JLab, BES, LHCb, BELLE) or future facilities (Belle2, PANDA) will extend our knowledge into the strange and heavy quark sector, answering the question whether the same dynamics is at work in the single- and multi-strange sector or whether this might change for baryons including heavy quarks. This common effort will provide us with an answer to the question of how the strong interaction produces its bound states. One of the most spectacular results is the recent discovery of a heavy pentaquark state at LHCb. While further, more refined analyses of the present data have confirmed the earlier findings, new data from the next LHC run will be needed to understand the exact nature of these structures thus corroborating the evidence that quarks can aggregate in groups of five.

Recent theoretical studies of hadrons have focused largely on lattice QCD and Effective

Box 3: Meson form factors and the muon anomalous magnetic moment

The muon anomaly $a_\mu=(g-2)_\mu/2$ is a low-energy observable, which can be both measured and computed within the Standard Model with extremely high precision (see the discussion in WG 5). The present experimental value stems from the BNL E821 experiment and corresponds to an uncertainty of 0.54 ppm. It deviates from the SM prediction, whose accuracy is even slightly better, by more than three standard deviations. While the discrepancy is not sufficient to claim the observation of "new physics", it calls for a concerted international effort to increase the accuracy of both the direct measurement and the SM prediction. New direct measurements of $(g-2)_\mu$ are being prepared at Fermilab and JPARC and are scheduled to start taking data in 2017 and 2019, respectively. The goal is to reduce the uncertainty on the direct measurement by a factor of four. In order to allow for an interpretation of the improved direct measurements, improvements in the overall accuracy of the SM prediction are mandatory.

The SM prediction is limited by hadron-induced quantum corrections that cannot be estimated in perturbation theory. While the hadronic vacuum polarisation (HVP) contribution can be related to hadronic cross section measurements via a dispersion relation, so far, one had to rely mostly on model estimates to quantify the hadronic light-by-light scattering (HLbL) contribution. Recently, phenomenology-driven approaches were suggested for HLbL, relying on meson transition form factor data. Therefore, meson form factors not only provide insights into the structure of hadrons, but are also of utmost importance to increase the precision of the SM estimate for the HVP and HLbL contributions to $(g-2)_\mu$. The exclusive channel $e^+e^- \to \pi^+\pi^-$, which is determined by the pion vector form factor, contributes almost 75% to the dispersion relation for HVP. The importance of this channel and other channels with higher multiplicities has led to detailed experimental studies of the hadronic cross section at electron-positron colliders.

For the HLbL contribution, a dispersion-theory-based strategy was only recently suggested. In this approach, the relation to experimental data is much more subtle, and so is the diversity of the required data input. The most relevant contribution comes from pseudoscalar pole terms, which are linked to meson transition form factors, describing the coupling of the neutral mesons π^0, η and η' to two photons. A new campaign of precision measurements of these form factors is currently ongoing at various hadron facilities worldwide. Finally, also large-scale efforts using lattice QCD as well as Dyson-Schwinger equations are currently ongoing to determine the HVP and HLbL contributions.

Field Theories. In the baryon sector lattice simulations have achieved significant progress in computing the masses of the ground-state and the excited-state octet and decuplet baryons from first principles. In the meson sector the most significant progress came from the development and application of new techniques to study excited states and resonances (Figure 2) and to address bound states close to the strong decay threshold. An important ingredient is the ability to perform simulations at the physical pion mass, which largely eliminates the systematic effects associated with chiral extrapolations.

Much progress has also been made in describing the spectrum and dynamics of excited baryonic states through coupled-channel studies based on effective hadronic Lagrangians constrained by QCD symmetries. These approaches, as well as tools like partial wave analysis are still the main tools for interpreting the tremendous amount of new data generated at JLab, ELSA and MAMI.

Significant progress has been achieved in calculating higher-order perturbative corrections in EFT descriptions of heavy quark systems. This allows for precise determinations of mass spectra and transitions, as well as the strong coupling constant and the heavy quark masses. EFTs are also being formulated for the description of exotic states (Figure 3).

Within the framework of Dyson-Schwinger/Bethe-Salpeter equations substantial progress has been made in the solution of the three-body Faddeev equation which replaces the previously employed quark-diquark models. The treatment of excited states is now possible, and the exploration of the baryon spectrum in this framework has begun. Other approaches include the string-theory-motivated AdS/QCD model, describing strong interactions in terms of a dual gravitational theory.

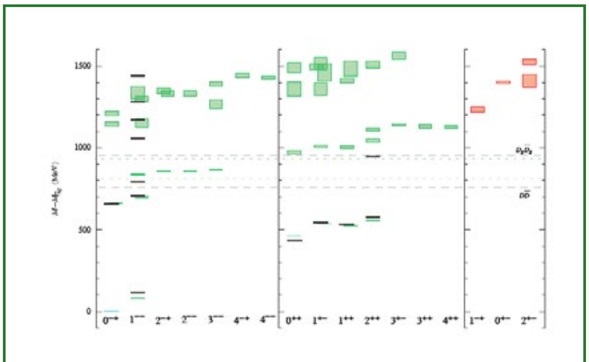


Figure 2: Charmonium spectrum as determined in Lattice QCD (JHEP 1207 (2012) 126.)

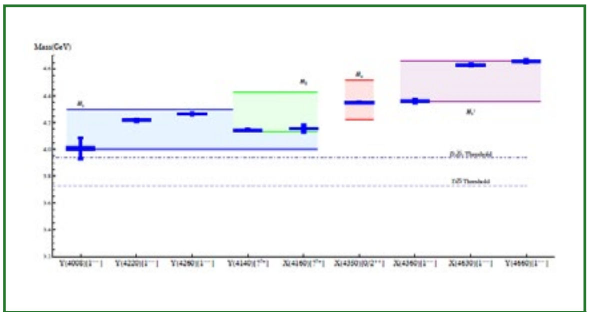


Figure 3: Mass spectrum of experimentally observed neutral mesons (solid blue points) compared to EFT predictions for heavy hybrid states (coloured bands) (from PRD 92 (2015) 114019).

Future Prospects

The next generation of experiments should move from serendipitous discoveries of individual new states to the systematic study of spectral properties and patterns. More work is required to understand the underlying dynamics of resonances. This will involve the use of a wide range of experimental facilities, including photon, electron and meson beams, e^+e^- colliders and antiproton-proton annihilations.

Experiments will need to continue to improve on the statistical accuracy of measurements (higher luminosity and/or larger acceptance). In addition, the requirement to access spin degrees of freedom is crucial, so beam and target polarisation, as well as the determination of the polarisation of outgoing particles in a reaction, will be vital. An improvement in detector performance will open up other possibilities, such as the investigation of poorly known sectors such as strange-rich states (Λ's, Σ's and cascades).

As experiments get more complex, it will be necessary to develop more advanced statistical methods and sophisticated analysis tools that can be used to identify new resonant states and infer their properties. Experiments are also generating larger data sets, which creates new challenges for data handling and processing. A key component of this work will be the close cooperation between experimentalists and theorists in activities such as partial wave analysis. A joint venture, called JPAC, has already started.

Box 4: Functional Methods

Functional approaches to QCD, including Dyson-Schwinger and Exact Renormalisation Group equations, are formulated at the level of the Green's functions of the theory, which contain all information on the physical content of QCD. Applications include determinations of the hadron spectrum, form factors and observables describing decays, and other processes involving hadrons such as Compton scattering or pion-nucleon interactions. Functional equations come in the form of an infinite tower of relations that couple Green's functions to one another in a hierarchical fashion. These exact equations need to be approximated (truncated) in practice to allow for a numerical treatment. Truncation schemes at very different levels of sophistication have been developed: very simple approximations allow for making contact with quark model calculations; highly sophisticated and numerically demanding schemes admit a direct comparison with lattice QCD.

Phenomena of QCD in the strongly interacting regime like confinement and dynamical chiral symmetry breaking have been and are still being studied using these methods. Bound state equations are derived which allow for the determination of the spectrum and the wave functions of mesons and baryons including also "exotic" objects like glueballs and tetraquarks. The gauge-invariant coupling of external currents allows for the extraction of form factors and production processes. One of the benefits of functional methods is the possibility to maintain Poincaré covariance. Thus they can be used in the light and heavy quark region alike, allowing for fruitful interactions with chiral perturbation theory and heavy quark effective theory, respectively. Systematic comparisons with other approaches including lattice QCD offer a very high potential for the identification of the physical mechanisms behind the observable phenomena.

HADRON STRUCTURE

It is the main purpose of hadron and nuclear physics to obtain an understanding of the properties of strongly interacting matter in terms of the basic constituents. A cornerstone in this enterprise is the description of the internal structure of the nucleon, which is one of the most intensely studied composite particles. Despite the large amount of available data and significant progress in the development of theoretical descriptions, unravelling the inner structure of the nucleon still presents enormous challenges, and the field continues to produce surprises that call for new experiments and theoretical studies. Perhaps the most spectacular recent example is the "proton radius puzzle", i.e. the observed inconsistency between the proton radius determined via the Lamb shift in muonic hydrogen and the corresponding measurement in ordinary hydrogen. The latter is consistent with the estimate derived from the proton's electromagnetic form factor measured in electron-proton scattering.

While the momentum of a fast moving proton is very precisely understood in terms of the momentum fraction of its constituents, the same cannot be said of our understanding of the proton spin. The most recent data from the COMPASS experiment at CERN have demonstrated that valence quarks account for only one third of the proton's spin. It is still unclear whether the remaining fraction can be firmly attributed to the contributions from the spin of gluons and virtual quarks, as well as those related to the angular motion of all the proton's constituents. This so-called "proton spin puzzle" has triggered a worldwide experimental research programme at the major laboratories. Its long-term goal is the generation of a comprehensive database on a number of key quantities, such as form factors, structure functions, generalised parton distributions (GPDs) and transverse momentum distributions (TMDs) all of which are crucial in order to obtain a quantitative understanding of the proton's spin, magnetic moment and three-dimensional internal structure in terms of quarks and gluons.

A detailed understanding of hadron structure is not only interesting in its own right but also indispensable for exploring the limits of the Standard Model. For instance, the overall precision of measurements performed at the LHC and other hadron colliders depends on the precise knowledge of parton distribution functions. Another example is the strangeness form factor of the proton which probes its sea quark structure. This quantity currently limits the accuracy of precision measurements of the electroweak mixing angle at low energies, which serves as a probe for physics beyond the SM.

A major experimental programme is under way to determine form factors, polarisabilities, parton distribution functions, GPDs and TMDs. This will provide the experimental data for detailed analyses based on the theoretical concepts that have been developed for many years. A powerful tool for the theoretical description of structural properties is QCD factorisation, which allows for the separation of energy scales characterising the hard and soft contributions to the relevant scattering amplitudes. While the former can be treated in QCD perturbation theory, the soft part is intrinsically non-perturbative and must be evaluated using phenomenological models. There has also been a major effort to determine structural properties from first principles using lattice QCD, with the main activities focussed on determinations of electromagnetic form factors, quark momentum fractions and the axial charge of the nucleon.

Recent achievements and state of the art

Electromagnetic form factors and the proton radius puzzle

The slope of the proton's electric form factor at zero momentum transfer as measured in electron-proton scattering (see Figure 4), as well as measurements of the energy levels in the hydrogen atom are well known methods to measure R_E, the charge radius of the proton. Estimates for R_E extracted either from electron-proton (*ep*) scattering data or from precision spectroscopy of ordinary, electronic hydrogen agree well with each other, which is reflected in the CODATA recommended value of R_E=0.87551 fm. The situation changed dramatically when first results for the Lamb shift in muonic hydrogen were reported, which allowed for an extremely precise extraction of R_E in strong disagreement with the previous determinations. It has been shown that hadronic corrections from two-photon exchange, which are related to the magnetic polarisability of the proton, are too small to explain the proton radius puzzle. The experimental situation concerning the determination of R_E from atomic spectroscopy is discussed in detail in WG 5.

Among the possible origins of the puzzle are systematic effects in the experimental determinations

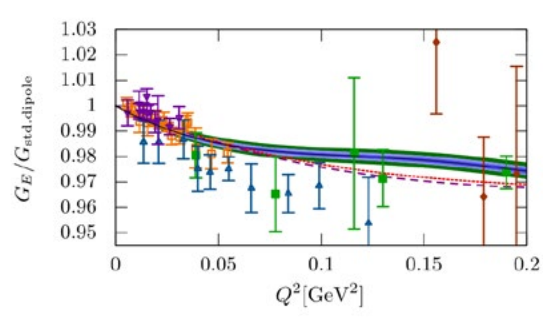


Figure 4: Compilation of data for the proton electric form factor G_E (PRC 90 (2014) 015206 and references therein). The charge radius is extracted from the slope at Q^2=0.

that are unaccounted for. This concerns both the extrapolation of *ep* scattering data to zero recoil, as well as the determination of hydrogen spectra. An alternative explanation is based on missing or unknown hadronic effects in the *ep* scattering process. Finally, the observed discrepancy could be due to physics beyond the Standard Model, in the form of light scalar or vector particles in the MeV mass range, or large extra dimensions.

The current state of affairs calls for a dedicated, cross-disciplinary programme involving experimental hadron and atomic physics, supported by renewed efforts in hadron and particle theory, as well as lattice QCD. PSI has embarked on a rich programme to measure the charge radii of a range of light nuclei in muonic systems. This is complemented by new and improved measurements of atomic transitions in electronic hydrogen. Furthermore, a new generation of precision measurements of electromagnetic form factors at very low momentum transfers will be performed, using the ISR method at MAMI, PRad at JLAB, and the new MAGIX spectrometer at MESA. The proton radius puzzle will also be addressed by the MUSE experiment at PSI, which will determine electromagnetic form factors in scattering. These experimental activities will be accompanied by new theoretical investigations as well as calculations of nucleon form factors in lattice QCD.

Nucleon form factors

The electromagnetic form factors (FFs) of hadrons, most prominently of nucleons, have been studied with ever increasing accuracy over the last 50 years. The main tool has been elastic lepton scattering, which probes spacelike momentum transfers. Timelike momentum transfers are accessible in annihilation processes. Due to their analyticity in the 4-momentum transfer Q^2, spacelike and timelike FFs can be connected through dispersion relations. In the spacelike region, they allow for a spatial imaging of quarks in a hadron, whereas in the timelike region they encode the excitation spectrum of spin-1 mesons. These two complementary aspects of hadron structure demand a determination of the electromagnetic FFs over the full kinematical range of Q^2.

On the theory side, a wide variety of models based on effective degrees of freedom have been used to estimate nucleon FFs. Form factor data also provide benchmarks for lattice gauge theory. Furthermore, spacelike FFs yield the first moment of GPDs (see below). Dispersion relations are used to analyse the structure of the FFs in the spacelike and timelike regions simultaneously.

For electric and magnetic FFs of the proton and neutron at spacelike momentum transfers, there are active experimental programmes at MAMI (at lower momenta) and at JLab (with higher momenta). The availability of CW electron beams at high current and high polarisation allows measurements with unprecedented accuracy up to high energies due to the large available luminosities and – for experiments with polarisation – large figures of merit.

There is continued interest in nucleon FFs, both in experiment and theory, because of the unresolved issue regarding the determination of FFs via the polarisation transfer method which shows that the ratio of electric and magnetic FFs, G_E/G_M, for the proton deviates from unity, in contrast to the results derived from the Rosenbluth separation technique. While it is still debated whether or not this discrepancy is connected with two-photon exchange amplitudes, it has been shown that the polarisation transfer method is much less sensitive to those effects and therefore yields cleaner FF extractions. The question of the importance of the two-photon exchange amplitude in elastic scattering has triggered a whole new field of research. Several dedicated programmes, comparing elastic scattering of electrons with elastic scattering of positrons from protons are underway at JLab, at the Novosibirsk e^+e^- collider VEPP2000, and at the Doris ring at DESY.

In the timelike region, where the FFs are complex functions of Q^2, the most precise experimental data have come from the BaBar experiment at the SLAC B-factory, via the process $e^+e^- \to \bar{p}p$, and from antiproton annihilation experiments at LEAR. The limited statistics of current data does not allow for an independent extraction of the timelike electric and magnetic FFs. Moreover, the present error on the ratio of electric over magnetic FF in the timelike domain is larger by almost two orders of magnitude compared to the spacelike region.

While the BESIII experiment at the BEPCII e^+e^- collider (IHEP, Beijing) devotes a significant part of its data taking to electromagnetic form factor measurements, the PANDA experiment at GSI/FAIR will make a real difference in the study of electromagnetic FFs in the time-like region. PANDA offers a unique opportunity to determine the moduli of the complex FFs in the time-like domain over a wide range of momentum transfers from antiproton annihilation reactions, with expected statistical errors 20 to 50 times smaller than those on present data.

Baryonic transition form factors

Extracting the electromagnetic amplitudes for the transitions between ground and excited nucleon states, over a broad range of Q^2 gives insight into the evolution of meson-cloud effects and how dynamically-generated masses emerge from the asymptotically-free, nearly massless quarks of QCD. Just like the elastic form factors mentioned above, transition form factors are expected to be analytical functions of Q^2, connected in spacelike and timelike regions by dispersion relations. The space-like region has been intensively explored using meson electro-production experiments for Q^2 up to about 5 GeV^2. In recent years, the CLAS detector at JLab has measured transition form factors for many baryon resonances (up to N(1720) and Δ (1700)). Furthermore, following the 12 GeV upgrade of JLab the new CLAS12 detector will soon extend these form factor measurements to 10 GeV^2. To explore the basically unknown timelike region, the HADES collaboration at GSI/FAIR, investigates electromagnetic baryonic transitions at low positive Q^2 by studying the Dalitz decay of baryonic resonances. Since vector meson poles play a prominent role in electromagnetic interactions in this regime, their study also provides constraints for the interpretation of dilepton spectra measured in heavy-ion experiments in terms of in-medium distortion of the ρ-meson spectral function which is one of the very few possibilities to experimentally study chiral symmetry restoration in hot and dense matter (see section WG 2 "Phases of Strongly Interacting Matter").

Polarisabilities

While form factors provide the static distributions of charge of a particle, polarisabilities describe the deformation of the distribution by an external electromagnetic field. The proton and the neutron, each with spin–1/2, possess two scalar and four spin polarisabilities. While the scalar electric polarisability of the proton has been already relatively well determined, the magnetic and spin polarisabilities have been measured recently with a good precision at MAMI in real Compton scattering, using linearly and circularly polarised photons on transversely and longitudinally polarised proton targets. The neutron polarisability will also be studied at MAMI through a comparison of Compton scattering from high-pressure ^{3}He and ^{4}He targets and from a deuterated butanol target. An extensive programme to study generalised proton polarisabilities in virtual Compton scattering has been performed at MAMI, which completes earlier measurements performed at MIT/Bates and JLab. In contrast, for charged pions the experimental situation is more difficult since they are not available as fixed targets. Although different techniques exist, measurements are affected by large experimental and theoretical uncertainties. The most precise result has been obtained recently by COMPASS at CERN using a pion beam and the Primakoff technique. The result is in tension with previous measurements, but in agreement with the expectation from chiral perturbation theory. Another method using the reaction $\gamma\gamma\to\pi\pi$ will be investigated at BESIII and at JLab.

A feasibility study to measure kaon polarisabilities is being performed at CERN, using the radio-frequency separated high-intensity antiproton/kaon beam, which allows for an increase of the beam intensity by one to two orders of magnitude compared to the current COMPASS experiment. This will provide unique opportunities to accurately determine kaon polarisabilities.

Parton Distribution Functions

In the non-perturbative regime of QCD, the internal quark-gluon structure of hadrons is described in terms of a well-defined hierarchy of correlation functions as the unpolarised and polarised parton distribution functions (PDFs). These functions specify the number density of quarks q and gluons γ carrying a momentum fraction x of the total hadron momentum and having a certain spin orientation inside the hadron. While QCD does currently not allow for a first-principles calculation of the quark and gluon distributions, they can be determined via evolution equations in terms of x and the energy transfer Q^2, respectively. The successful prediction of the dependence of PDFs on x and Q^2 has been one of the great triumphs of QCD.

In recent years also LHC pp data have been used in global analyses. Since the discovery of the Higgs boson, the LHC physics programme is mostly driven by the search for new physics. Precise theoretical predictions of background processes are needed for a discovery, whereas accurate predictions of new phenomena are needed for the interpretation of exotic physics signals or for verification of Higgs boson properties. This is why the precise knowledge of PDFs and their uncertainties is essential at the LHC.

Measurements of the total and differential cross sections of W and Z production, differential Drell-Yan cross-sections, W-charged lepton asymmetry, inclusive jet cross sections, as well as reactions related to top production are used successfully to validate NNLO predictions for PDFs and further constrain their uncertainties. In particular, the valence distribution of the d quark and the distribution of the s quark are better constrained with LHC data than from DIS measurements only. The latest data at $\sqrt{s}=13$TeV, as well as precise measurements of M_W and $sin^2\theta_W$ will be important to increase the precision further.

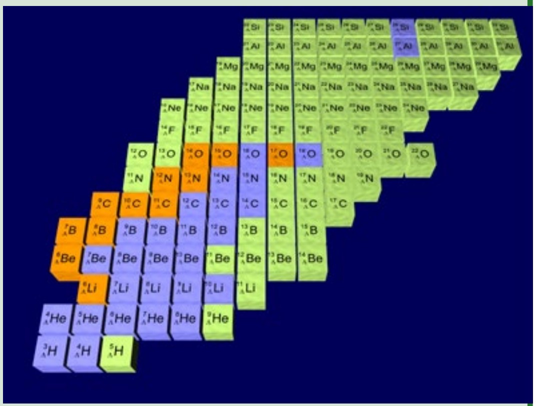
Two long-standing puzzles are of particular interest for the present experiments and for the planning of the future ones:

The first concerns the proton wave-function at small x, which is dominated by gluons and referred to as the Colour Glass Condensate (CGC). The question arises whether the gluon and quark densities can grow indefinitely at small x or whether a saturation regime is encountered. There are indications from HERA, RHIC and LHC that gluons will start to recombine, thereby reaching the saturation regime, but an independent confirmation is still missing. The main difficulty comes from the fact that the kinematical regime is difficult to realise experimentally: smaller values of x can be either reached by the expensive option of increasing the centre-of-mass energy or by using heavier nuclei. Therefore, the best short-term option to pin down the CGC is by performing DIS experiments on nuclei at a future Electron-Ion Collider (EIC), a project currently under consideration in the US.

The second is the "proton spin puzzle", i.e. the question how the spin of the proton can be decomposed in terms of its constituents. DIS experiments at CERN, DESY and JLab cannot fix the gluon contribution Δg due to the limited kinematic range, but have accessed Δg directly through the process of photon-gluon fusion. COMPASS has measured a small value of Δg in the accessible range of x. The most precise measurement of Δg comes from RHIC using processes that receive substantial contributions from gluon-induced hard scattering. Recent global analysis using data from the PHENIX and STAR experiments have shown a substantial integrated gluon contribution in the covered x-region. Furthermore, measurements from PHENIX on longitudinal single-spin asymmetries in $W^\pm$ and Z^0 boson production have provided better constraints on the polarisation of sea quarks and anti-quarks. Recently, the COMPASS collaboration at CERN presented results for g_1^p and A_1^p, increasing the statistical precision by a factor of two. In order to address the proton spin puzzle the accuracy in the determination of polarised PDFs must be increased further. This can be achieved by extending to kinematic coverage to even smaller values of x, preferably at the EIC.

Box 5: Hypernuclei

Recently, hypernuclear spectroscopy with heavy ion induced reactions has been successfully performed by the HypHI collaboration at GSI. They have shown that the lifetime of the lightest hypernucleus, ${}^{3}_{\Lambda}\mathrm{H}$, is significantly shorter than the Λ-hyperon, also reported by hadron-collider collaborations. A short ${}^{3}_{\Lambda}\mathrm{H}$ lifetime has not yet been explained by any theory so far and remains as a puzzle. A signal indicating the existing a neutral strange nucleus, ${}^{3}_{\Lambda}\mathrm{n}$ (nnΛ), has been reported, which is still under debate and it requires experimental confirmation. By solving these puzzles with more data on exotic hypernuclei toward nucleon drip-lines, one can deduce essential information on the baryon-baryon interaction under SU(3) including three-body forces. Exotic hypernuclei can only be studied with heavy ions at GSI and FAIR. With these experiments, Europe will play an essential role in nuclear physics with strangeness.



Hypernuclear chart expected to be synthesized and studied at GSI and FAIR. Blue boxes indicate known hypernuclei while orange and green coloured boxes show cases to be populated with 10^4 and 10^3 reconstructed events per week, respectively.

Generalised Parton Distributions (GPDs) and Transverse Spin and Momentum-Dependent Distributions (TMDs)

Our knowledge of nucleon structure has drastically improved in the last few years thanks to the vigorous activity revolving around Generalised Parton Distributions (GPDs) and Transverse Spin and Momentum-Dependent Distributions (TMDs). These new functions complete the information from form factors and parton distributions, providing a three-dimensional description of the internal structure of hadrons. GPDs and TMDs correlate either the transverse position or transverse momentum or spin of partons with their longitudinal momentum. They open the exciting possibility of determining the spatial distribution of quarks and gluons in the nucleon as a function of the parton wavelength and of providing access to the orbital angular momentum of quarks and gluons.

Two main processes have been identified as giving the best access to GPDs: Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). GPDs are process-independent universal quantities. A factorisation theorem has been proven for DVCS and for longitudinally polarised photons in DVMP, providing a solid theoretical basis for GPD measurements through hard exclusive reactions. DVCS and DVMP have been explored in recent years at several experiments: HERMES used 27 GeV electron and positron beams, H1 and ZEUS analysed collisions of 820 GeV protons with 27 GeV electrons or positrons, while JLab has increased the energy of its electron beam from 6 to 12 GeV. Accurate cross-section measurements have shown indications of leading-twist dominance in the accessible kinematic regions. The high precision of the data has stimulated further theoretical analyses to understand the fine details. A variety of beam and target spin asymmetries has been used to constrain models and build GPD parameterisations that have delivered the first 3D images of nucleon structure. In the next few years the most important data will come from the JLab 12 GeV upgrade and the GPD programme at COMPASS. The new kinematic regime accessible at JLab (see Figure 5) and the extremely high luminosity will allow for a systematic and multi-dimensional exploration

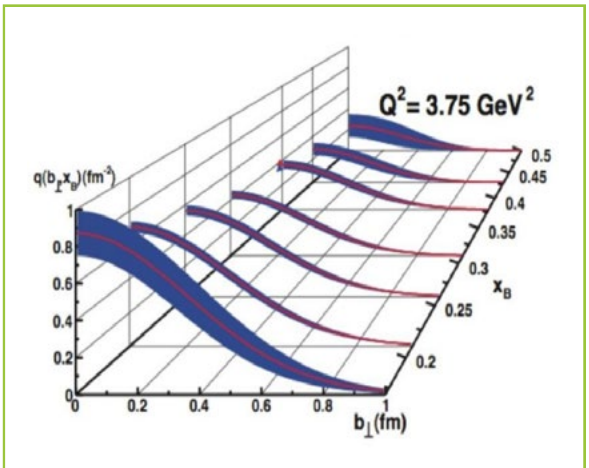


Figure 5: Nucleon transverse profile at different values of x. The bands show the projected uncertainties from the JLab experiments at 12 GeV.

Experiment/Lab	Running Time	Reactions for TMDs	Reactions for GPDs	$\mathcal{L}$ $(cm^{-2}s^{-1})$	$\sqrt{s}$ GeV
Completed					
Hermes/ DESY	1996-2007	$e^-[p^\uparrow, (p,d)_{\mathrm{unp.}}]$	$(e^\pm)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\mathrm{unp.}}]$	$> 10^{31}$	7
H1, ZEUS/ DESY	1996-2007		$(e^\pm)^\rightarrow p$		
BaBar/ SLAC	1999-2008	e^+e^-		$> 10^{33}$	10
Belle/ KEK	1999-2010	e^+e^-		10^{34}	10
Hall ABC/JLab	2005-2014	$e^-[(p,n)^\uparrow, (p,d)_{\mathrm{unp.}}]$	$(e^-)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\mathrm{unp.}}]$	10^{38}	3
Running					
COMPASS/ CERN	2002→	$\mu^+[(p,d)^\uparrow, (p,d)_{\mathrm{unp.}}]$ $\pi^-[p^\uparrow]$	$(\mu^\pm)^\rightarrow[p_{\mathrm{unp.}}]$	$> 10^{31}$	17-19
BesIII/ BEPC	2009→	e^+e^-			4
Hall ABC/ JLab12	2016→	$e^-[(p,n)^\uparrow, (p,d)_{\mathrm{unp.}}]$	$(e^-)^\rightarrow[(p,d)^{\uparrow\rightarrow}, (p,d)_{\mathrm{unp.}}]$	10^{38}	5
Star, Phenix/ RHIC	2001→	$p^\uparrow p^\uparrow$		10^{32}	200-500
Foreseen					
Belle2/ KEK	>2016	e^+e^-		10^{36}	10
E1039/FLab	>2020	$pp^\uparrow$		$> 10^{35}$	15-30
COMPASS/ CERN	>2020	$\mu^+d^\uparrow$ $(\bar{p},K)[(p,d)^\uparrow]$	$(\mu^\pm)^\rightarrow[(p,d)^{\uparrow\rightarrow}]$	$> 10^{31}$	17-19
PANDA/ FAIR	>2025	$\bar{p}^{(\uparrow)}[p^\uparrow]$		10^{32}	5
EIC	>2025	$e^-(p,n,d)^\uparrow$	$(e^-)^\rightarrow(p,n,d)^{\uparrow\rightarrow}$ $(e^-)^\rightarrow(p,n,d)_{\mathrm{unp}))}$.	$> 10^{34}$	25-145
SPD/NICA/JINR	>2020	$p[(p,d)^\uparrow]$		10^{31}	12-27
AFTER/CERN	>2020	$p[(p,d)^\uparrow]$		$> 10^{33}$	115

Table 2: A compilation of previous, running and planned experiments accessing TMDs and GPDs. Targets for fixed target experiments are in square brackets. Only reactions with lepton beams are reported here for GPD determinations.

of GPDs, reaching values of the momentum transfer much higher than before. A dedicated experimental programme is planned in Hall A with existing equipment, in Hall B with the new CLAS12 spectrometer and in Hall C with the addition of a Neutral Particle Spectrometer. The COMPASS experiment will study DVCS and DVMP with polarised muon beams at 160 GeV and explore the region of intermediate x between H1/ ZEUS and HERMES/JLab. The increased luminosity of upcoming experiments will make it possible to study GPDs through complementary channels such as timelike Compton scattering, the crossed reaction of DVCS, as well as Double DVCS, where both the initial and final photons are virtual. The large amount and precision of the data from all these different experiments will revolutionise our current understanding of hadron structure

TMDs are complex objects and must be accessed through global analyses of complementary processes (such as SIDIS, Drell-Yan, e^+e^- annihilation into hadrons and hard polarised hadron-hadron scattering) in order to disentangle their flavour and kinematic dependences. Two striking effects have been demonstrated recently. One is the Collins mechanism that correlates the spin of the fragmenting quark with the azimuthal angle of hadrons produced in processes like SIDIS, $e^+e^-\rightarrow$hadrons. The other is the correlation between the spin of a transversely polarised nucleon and the intrinsic transverse momentum of the quarks, giving rise to the so-called Sivers asymmetry. These measurements performed by the HERMES and COMPASS collaborations, as well as the JLab experiments have shown pronounced spin-orbit and quark-gluon correlations in kinematic regions where the valence quark contributions are significant. One of the most fascinating predictions of the TMD approach is the sign change of the Sivers and Boer-Mulders TMDs between SIDIS and Drell-Yan reactions, which represents a test of QCD factorisation. An experimental verification that the leading-order TMD formalism is correct is still missing, which is one of the most urgent goals of the present experimental activity. The non-trivial universality of the Sivers TMD will be verified by comparing the Sivers asymmetry from SIDIS with the one from Drell-Yan at COMPASS and planned experiments such as PANDA at FAIR, AFTER at CERN, SPD at NICA. A precise study of the distribution of transverse quark momenta is another pressing issue for investigations of TMDs. Such a programme has started only recently with the availability of multi-dimensional results on hadron multiplicities and their azimuthal dependences by HERMES and COMPASS. These analyses must be extended to e^+e^- colliders to fully disentangle the contributions of transverse hadron and quark momenta in hadron lepto-production. Precise information on the fragmentation process is expected in the near future thanks to the ongoing BELLE-II and BESIII upgrades, complementing SIDIS measurements. Kaons provide enhanced sensitivity on strangeness. A significant step towards the full tomography of the nucleon will come from the realization of the EIC that will greatly extend the coverage in x and Q^2 while significantly increasing at the same time the accuracy of the measurements.

An overview of experiments to study TMDs and GPDs is presented in Table 2.

Future Prospects

While the measurement campaign for form factors and polarisabilities of the nucleon will continue at the Mainz Microtron (MAMI) there are plans at Mainz for a dedicated new experiment (MAGIX) which is aimed at penetrating the very low-Q^2 regime for the determination of the electromagnetic form factors of the proton. This will allow for a much more precise determination of the proton radius in *ep*-scattering. Furthermore, planned measurements of the weak charge of the proton will complement the efforts at JLab.

At CERN the upgraded COMPASS experiment has started data taking and will produce new results for GPDs, TMDs, as well as pion and kaon polarisabilities. The COMPASS Collaboration is developing plans for future polarised DVCS and SIDIS measurements, together with new RF separated antiproton and Kaon beams that can be used both for spectroscopy and for polarised Drell-Yan measurements. Parton distribution functions, GPDs and TMDs will also be measured at JLab, where the 12 GeV upgrade of the accelerator has been completed. In the next years JLab will be capable of delivering a precision mapping of TMDs and GPDs in the valence region complementary to the measurements performed at HERMES and COMPASS.

PANDA at FAIR and SPD at NICA will deliver measurements of TMDs from Drell-Yan reactions complementary to similar experiments at higher energy. Moreover, new hadronic matrix elements called transition distribution amplitudes (TDAs) could be probed at antiproton-proton facilities such as FAIR, provided that factorisation for these channels can be proven.

The large communities working on hadron structure both in Europe and the US are working towards and eagerly waiting for the approval of the first polarised Electron-Ion Collider (EIC). This machine will enable precision measurements over a largely extended kinematic phase-space with light polarised and heavy unpolarised ions. The EIC will be capable of accessing the gluon content of the proton and make significant progress on the knowledge of the proton spin content, TMDs and GPDs. It may also advance our understanding of the non-perturbative structure of the strong interaction by discovering evidence for the mixed quark-gluon condensate.

HADRONIC INTERACTIONS

A profound knowledge of hadron-hadron interactions is required for high-precision SM predictions and for our understanding of the structure of matter at the femtometer scale. This concerns both the emergence of hadrons from fundamental constituents and the formation of more composite structures like atomic nuclei. In particular, the longest-range forces are mediated by the lightest hadrons, the pions. Their special role is intimately linked to QCD by chiral symmetry.

The exploration of the intrinsic structure of hadrons cannot be disentangled from hadron-hadron interactions, as the effects of creating additional virtual particles become significant. Thus the study of the structure of a specific hadron by a specific probe involves the interplay between a target-independent, universal coupling of the probe to the lightest virtual particles, and the coupling of the latter to the target of interest. A model-independent tool to link the universal to the target-specific aspects is provided by dispersion theory, which in turn requires the experimental determination of various reaction amplitudes with high precision.

Strange quarks are light enough so that the replacement of a light (up or down) by a strange quark does not radically alter a hadronic system. On the other hand, strange quarks are heavy enough that techniques designed to analyse light-quark systems reach their edge of applicability. Kaon, hyperon and hypernuclear physics provide a highly attractive and challenging research field, offering the opportunity to develop appropriate and precise methods for studying strongly interacting systems.

Recent Achievements, Hot Topics and Future Prospects

Improving the precision of SM predictions and understanding the structure of hadrons, nuclei and hyper-nuclei calls for a thorough experimental and theoretical investigation of pion-pion and pion-kaon, pion-nucleon and kaon-nucleon interactions together with nucleon-nucleon, hyperon-nucleon and nucleon-antinucleon interactions.

A combination of high-quality experimental data, dispersion relations, chiral perturbation theory and lattice QCD has made pion-pion scattering one of the theoretically most rigorously understood examples of hadron-hadron interactions. The leading partial waves are known very accurately up to invariant masses of at least 1.1 GeV. The pion-pion system is also a test bed for hadron spectroscopy, as a dispersive representation allows for the extraction of the masses and widths of the lightest resonances in QCD, the $f_0(500)$ and the $\rho(770)$, with excellent precision from their respective pole positions in the complex energy plane. The current state of the art is to turn the knowledge of pion-pion scattering into a tool for many other applications, using the universality of final-state interactions: This includes the determination of light quark mass ratios from $\eta \to 3\pi$, the analysis of chiral low-energy constants in K_{e4} decays, as well as the study of various form factors that are highly relevant for determining the hadronic contributions to the muon's anomalous magnetic moment, or for describing more complicated scattering processes involving pions, such as pion-kaon or pion-nucleon scattering.

The situation for the simplest meson-meson scattering process including strangeness, pion-kaon scattering, is far less satisfactory. Chiral perturbation theory with the heavier strange quarks is not as well behaved, and the experimental data is much less precise. Modern tau-charm factories offer opportunities for improvement: τ decays into $\pi K \nu_\tau$ already offer precision information on the vector channel, and the decay $D \to \pi K \ell \nu_\ell$ might allow for a model-independent extraction of pion-kaon phase shift information. Such progress would be highly desirable, not least due to the large number of mixed pion and kaon final states in many heavy-flavour decays that are important for precision studies of CP violation. Both systems, ππ and πK, are closely related, as the crossed channel of πK scattering describes the dominant inelasticity for the ππ s-wave, and therefore is an important ingredient for a better understanding of the spectrum of scalar-isoscalar resonances with its glueball candidates.

Pion-nucleon scattering, which has seen a remarkable revival recently, has a profound impact on nuclear physics, since it determines the two-pion-exchange contributions to nucleon-nucleon potentials, as well as the leading long-range three-nucleon force. The *t*-channel amplitude ($N\bar{N} \to \pi\pi$) is highly relevant for nucleon electromagnetic form factors. Furthermore, the πN amplitude is closely related to the pion-nucleon sigma term via a low-energy theorem due to Cheng and Dashen. The latter quantifies the light-quark contribution to the nucleon mass and is directly linked to the scalar couplings of the nucleon, whose precise determination is crucial for the interpretation of direct dark matter searches. The dispersive framework of Roy-Steiner equations has led to a remarkably accurate determination of the so-called sigma term of 59.1±3.5 MeV. This value is directly correlated with the pion-nucleon scattering lengths that are determined with high precision from pionic atom spectroscopy at PSI. However, it is in conflict with the most accurate calculations of the sigma term in lattice QCD, which seem to agree on a value closer to 40 MeV. A resolution of this conflict is urgently called for.

A lot of progress has been achieved for antikaon-nucleon scattering over the last few years, thanks partly to the new, much improved determination of ground state energy level shift and width of kaonic hydrogen by the SIDDHARTA collaboration (Figure 6). Unitarised chiral perturbation theory can now describe the resulting antikaon-nucleon scattering lengths consistently with scattering data. The antikaon-nucleon interactions are highly relevant for investigations of the two-pole structure of the Λ(1405) resonance. While the scattering lengths alone do not constrain the pole positions well enough, recent precise photoproduction data from CLAS have led to a clear preference for certain classes of solutions for the scattering amplitudes. Better data, as well as analyses using higher-order theoretical amplitudes are still desirable.

Chiral EFT for nuclear forces is advancing rapidly. While there is an ongoing debate about the renormalisation of these forces and the resulting expansion scheme, enormous progress has been achieved within Weinberg's original approach. In particular, fifth-order corrections to the two-nucleon force have been worked out and implemented. The resulting potentials demonstrate a good convergence of the chiral expansion and allow for an accurate description of low-energy *NN*

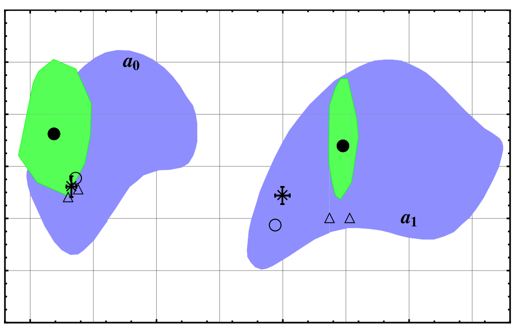


Figure 6: Illustration of the improved determination of antikaon-nucleon scattering lengths, based on unitarised chiral perturbation theory and the high-precision measurements of SIDDHARTA. The blue and green areas denote the 1 σ uncertainties (NPA 900 (2013) 51).

scattering data. They also provide clear evidence of the corresponding two-pion exchange contributions with all low-energy constants being determined from pion-nucleon scattering. This consistency between the πN and NN sectors shows that the theory has reached a remarkable level of maturity. Chiral EFT also offers a consistent framework for the construction of three- and four-body forces that appear at third and fourth orders in Weinberg's scheme, respectively. The existing *ab initio* nuclear structure and reaction calculations utilizing the leading chiral three-nucleon forces provide a clear indication of their importance for an accurate description of light nuclei. These studies are now extended to include higher-order corrections to the three-nucleon force. If supplemented by a quantitative uncertainty analysis, this will allow one to test the theory beyond the two-nucleon system. In particular, it remains to be seen whether the long-standing discrepancies in the three-body continuum can be resolved by the inclusion of the three-nucleon force.

Few-nucleon reactions with electroweak and pionic probes offer another exciting testing ground of chiral EFT. The corresponding two-nucleon electromagnetic and weak current operators are presently known to one-loop accuracy and have already been shown to provide a good description of the isoscalar and isovector charge and magnetic structure of light nuclei. The measurement of muon capture on the deuteron by the MuSun experiment at PSI will enable a precise determination of the short-range NN axial current, which plays an important role in the description of fundamental reactions of astrophysical interest.

Hypernuclei, i.e. nuclear systems with one or more bound hyperons, offer a unique opportunity to probe inner regions of nuclei and to study non-mesonic weak decays such as $\Lambda N \rightarrow NN$ since hyperons are free from Pauli blocking by other nucleons (see "box" on hypernuclei). Hyperons and their interactions with nucleons may also play an important role for the understanding of the interior of neutron stars. Hyperon-nucleon and hyperon-hyperon interactions have been studied at next-to-leading order using an SU(3) version of chiral EFT. An excellent description of the available hyperon-nucleon scattering data could be achieved. Also the leading three-baryon forces have been worked out, and the strength of the corresponding low-energy constants has been estimated. In the long term, a larger and better database for hyperon-nucleon scattering and light hypernuclei is needed in order to reliably pin down the values of the corresponding low-energy constants.

Significant progress has also been made in calculating the properties of light nuclei and hypernuclei from first principles within the framework of lattice QCD. While the results await further confirmation, most of the available lattice QCD studies indicate that the nuclear force becomes considerably more attractive for unphysically large values of the light-quark masses. In the regime with sufficiently heavy pions, pionless EFT has been demonstrated to provide an efficient approach for extrapolating the lattice QCD results to heavier systems beyond A=2–4. For pion masses closer to the physical point, the results of lattice QCD should eventually be matched to an appropriately tailored chiral EFT. In addition, one can use low-energy theorems for NN scattering to reconstruct the energy dependence of the amplitude at unphysical pion masses from the lattice-QCD results for the binding energy.

Chiral EFT methods are increasingly used to study interactions, whose elastic part is related to NN interactions by G-parity. There is a wealth of new experimental information on systems, in particular from J/ψ decays, often in connection with the quest for new resonances. However, many of the near-threshold enhancements can potentially be explained by conventional strong final-state interactions. A sound theoretical understanding of $N\bar{N}$ scattering is a prerequisite for the interpretation of timelike nucleon form factor data that will be obtained from PANDA. Hyperon-antihyperon systems will be investigated at PANDA as well, with high relevance for exotic spectroscopy with strangeness. Due to their self-analysing weak decays hyperon-antihyperon systems provide straightforward access to their spin properties without explicit polarisation. In the long run the successive weak decays of multi-strange hyperons have the potential to reveal CP violation in baryons, which may have implications for the baryon asymmetry of the universe.

As discussed in the section on hadron spectroscopy, a plethora of new states has been discovered over the last years, mainly in the area of heavy quarkonia. While some of them are manifestly exotic in the sense that they cannot be thought of as having simple $q\bar{q}$ or qqq quark structures (e.g., the Z_b states in the bottomonium sector, or the pentaquark candidates seen by LHCb), others seem to be at odds with the quark model as far as their properties are concerned (e.g. the X(3872)). A common feature of many of these states is their proximity to certain thresholds. The X (3872) lies very close to the sum of the D^{0*} and the $\bar{D}^0$ masses, while the two Z_b states are within a couple of MeV of the BB^* and the B^*B^*

thresholds, respectively. Such situations are well known from EFTs in nuclear physics: systems with bound or virtual states very close to threshold have a scattering length much larger than all other scales of the problem, and hence display several universal properties independent of the details of the short-distance interaction. The resulting large spatial extent makes the interpretation in terms of a significant molecular component unavoidable. The explanation of other "dynamically generated" states, also in the light-quark sector, relies on coupled-channel effects or even anomalous thresholds and triangle singularities. To fully explain the spectroscopy of these new, exotic states, an improved understanding of the interaction dynamics of the supposed constituents is mandatory.

LATTICE QCD

Lattice QCD calculations are instrumental for a quantitative description of hadronic properties in terms of fundamental interactions. Below we summarise the current status and provide an outlook for future work.

Hadron Spectroscopy: While there has been tremendous progress in determining the spectrum of baryons and mesons in lattice QCD, both in the light and heavy quark sectors (see Figure 2), additional efforts must be made in order to obtain more precise results on the excitation spectrum and perform more refined investigations of resonances and their decay properties. The use of a large basis of interpolating operators in conjunction with finite-volume techniques allows for detailed studies of mixing patterns among different states, as well as the determination of scattering phase shifts. Such calculations are becoming increasingly demanding since the numerical effort is largely driven by the complexity of the observable and its statistical noise, which is particularly severe for baryonic channels. Despite the development of efficient noise-reduction techniques, precise lattice calculations in hadron spectroscopy still require huge statistics.

The computational effort associated with the actual observables arises in addition to the generation of the gauge field ensembles, which has also become more expensive as realistic values of the dynamical quark masses – including the charm sector – are now used on a routine basis in lattice QCD. The requirement to control all sources of systematic error associated with the lattice formulation and the inclusion of electromagnetic effects makes a strong case for the development of supercomputers with exascale capabilities.

Hadron Structure: QCD factorisation is a key theoretical tool for the description of the scattering processes that probe the internal structure of the nucleon. It implies that scattering amplitudes can be separated into a "hard" and "soft" contribution. A non-perturbative approach such as lattice QCD must be applied in order to avoid any model dependence in the treatment of the soft part. One long-term goal of lattice QCD is to provide a comprehensive set of results for quantities such as form factors, structure functions and GPDs with controlled systematic uncertainties. This task is made more difficult due to a number of technical issues that arise in calculations in the baryonic sector, which have to be addressed and resolved. One important issue is the large intrinsic statistical noise of baryonic correlation functions that serve to extract the relevant physical information, such as masses and matrix elements. The large statistical errors impede the reliable isolation of the ground state, and thus the results extracted from baryonic correlation functions are prone to unwanted "contamination" from excited states in the same channel. The application of suitable noise reduction techniques that make it much cheaper to accumulate large statistics is a key development for achieving the long-term goal of lattice calculations. The statistical accuracy of iso-scalar quantities and observables that quantify the contributions from virtual quarks is also limited by the ability to compute so-called quark-disconnected diagrams efficiently. Significant progress has been achieved in the last few years, which, for instance, has lead to first results for the strangeness electromagnetic form factors of the nucleon.

Recent calculations have mostly focussed on a number of benchmark quantities that involve simple (forward) kinematics such as the quark momentum fraction $\langle x \rangle_{(u-d)}$ or the axial charge g_A of the nucleon, which are both important observables to describe the proton spin. While there are some discrepancies between lattice estimates and the experimental determinations of these quantities, it is likely that these are due to residual systematic effects related to unsuppressed excited state contributions.

Electromagnetic form factors of the nucleon have been another focus of recent lattice calculations. Thanks to the ability to control excited state contamination and to perform calculations near the physical pion mass the dependence of the form factors on the momentum transfer Q^2 can be reproduced. However, the current overall accuracy is not yet sufficient to clarify the proton radius puzzle or the discrepancy observed when using different methods to determine the ratio G_E/G_M. There are also efforts to predict the scalar and tensor charges of the nucleon, which are important quantities to constrain models for new physics based on additional scalar and tensor interactions. In addition, there have been exploratory calculations of GPDs in lattice QCD.

Among the main tasks in the years ahead is the increase in the overall precision of lattice calculations for form factors, quark momentum fractions and static charges of the nucleon. It is also the right time to tackle more complex observables such as GPDs and TMDs as new experimental data are awaited.

Hadronic Interactions: Lattice calculations are increasingly important for investigations of the dynamics of hadronic systems. A powerful technique (the so-called Lüscher formalism) has been developed, which allows for the determination of scattering phase shifts and scattering lengths, by computing the energy levels of multi-particle states in a finite volume. A number of results have been reported for meson-meson interactions, while the extension to meson-baryon and baryon-baryon systems is technically more involved, not least because of the noise problem inherent in baryonic correlation functions. An alternative formalism is based on the determination of the baryon-baryon potential via the Bethe-Salpeter amplitude which can be accessed in lattice simulations. There have been detailed studies on nucleon-nucleon interactions, including the determination of binding energies and scattering lengths. Several calculations have also focussed on hypernuclei and the possible existence of a stable H-dibaryon.

Another example that illustrates the impact of lattice QCD on hadronic interactions is the calculation of the πN sigma term, which is currently in conflict with the value extracted from the πN scattering length. Furthermore, lattice QCD becomes increasingly important for the determination of the hadronic contributions to the muon's anomalous magnetic moment, particularly the hadronic light-by-light (HLbL) scattering contribution. While *ab initio* calculations of the HLbL scattering part are still in an exploratory phase, it is also possible to use lattice QCD to test phenomenological models based on dominant sub-processes that are linked to meson-photon interactions.

PHYSICS PERSPECTIVES

European Perspectives

Over the past few years Europe has been playing a leading role in hadron physics thanks to dedicated experiments and facilities, like COMPASS, ELSA and MAMI. Furthermore, experiments whose primary goal is not the study of hadron physics, like LHCb, ATLAS and CMS at LHC, have been able to make significant contributions mainly to the field of hadron spectroscopy. In addition, the e^+e^- meson factory DAΦNE, at 1020 MeV centre-of-mass energy will continue operation with the KLOE 2 and SIDARTHA II detectors with a broad physics programme ranging from the study of CP and T violation in kaon decays to hypernuclei and kaonic atoms. HADES at GSI offers unique opportunities to determine baryon transition form factors in and reactions and to study hyperon resonances and pion-induced processes. HADES will be continued at SIS18 and later at FAIR. The next major step forward will require the HESR antiproton facility at FAIR and the PANDA experiment to be completed and become operational without further delay. With the operation of FAIR the leading role of Europe in the field of hadron physics will be established even more firmly. The main players in the field, present and future, are listed below.

COMPASS @ CERN

COMPASS is a high-energy physics experiment at the Super Proton Synchrotron (SPS) at CERN in Geneva, Switzerland. The purpose of this experiment is the study of hadron structure and hadron spectroscopy using high intensity muon and hadron beams.

ELSA @ Bonn

The Electron Stretcher Accelerator ELSA at Bonn University provides a beam of polarised and unpolarised electrons with a tunable energy of up to 3.5 GeV. Its hadron physics programme using the large acceptance CBELSA/TAPS and BGO-OD detectors is devoted to baryon spectroscopy via meson photoproduction using polarised beams and polarised targets. The CBELSA/TAPS experiment, which combines the Crystal Barrel and TAPS electromagnetic calorimeters, is ideally suited to investigate the photoproduction of neutral mesons decaying into photons. BGO-OD is a newly commissioned experiment at ELSA, consisting of a central BGO calorimeter and a large aperture forward magnetic spectrometer. This setup allow detection of complex final states with neutral and charged particles and is particularly suited for the study of vector meson and associated strangeness photoproduction.

MAMI @ Mainz

The Mainzer Mikrotron (MAMI) is an electron accelerator delivering beams of electrons and photons up to a maximum energy of 1.5 GeV. Many high-precision measurements of meson photoproduction near threshold have been performed and are planned for the future. In addition to being able to produce polarised beams, cryogenic target technology has allowed for the deployment of polarised targets, and recoil polarisation techniques have been developed. Results from MAMI nicely complement those from Bonn and JLab. MAMI is also a unique meson factory with world-class photoproduction rates for η, η' and ω-mesons. Furthermore, precision measurements of the kaon-nucleon interactions and of light hypernuclei are carried out at the A1 experiment.

HADES @ GSI and FAIR

HADES is operated at the SIS18 and was designed to investigate microscopic properties of resonance matter formed in heavy-ion collision in the 1–2 AGeV energy regime via e^+e^- and strangeness production. Also, the underlying processes are studied using beams of pions, protons and deuterons, providing a wealth of hadron physics measurements in the field of strange and non-strange baryon spectroscopy, as well as hadronic interactions and electromagnetic baryon transitions in the time-like region. HADES will soon be equipped by an electromagnetic Calorimeter and will be operated in future at FAIR with proton beams up to 30 GeV and ion beams up to 8 AGeV.

PANDA @ FAIR

The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. Antiprotons produced by a primary proton beam will then be stored into the High Energy Storage Ring (HESR) and collide with the fixed target inside the PANDA Detector. PANDA will study antiproton-proton interactions in the centre of mass energy range between 2.0 and 5.5 GeV and will be unique in the world in terms of beam momentum resolution and luminosity. The use of a general-purpose detector with excellent performance in terms of resolution and sensitivity will enable PANDA to carry out a comprehensive and far-reaching experimental programme from hadron spectroscopy to hadron structure and hadronic interactions, thus exercising a huge impact on the field. Given the recent positive developments of the FAIR project, PANDA can be expected to become operational in the first few years of the next decade.

LHC @ CERN

The Large Hadron Collider beauty (LHCb) experiment was designed to study matter-antimatter asymmetries through b-quark decays. After the reported discovery of a charmed pentaquark state, it has an important role to play in hadron spectroscopy. There are plans by the AFTER collaboration to run the LHC in fixed target more with and without polarisation. This will allow for probing rare proton fluctuations at large x, studies of vector boson production near threshold and studies of TMDs and the gluonic structure of the nucleon via Drell-Yan reactions.

NICA @ JINR

The Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research in Dubna, Russia, will provide important new opportunities for investigations of the nucleon spin via Drell-Yan processes. Longitudinally and transversely polarised proton and deuteron beams will become available, as well as a dedicated detector for spin physics.

Global perspectives

The most important experimental contributions to hadron physics outside Europe come from facilities in the United States (JLab), China (BESIII) and Japan (Belle2). They are briefly discussed in the following. Other significant contributions to hadron physics will come from the VEPP-2000 e^+e^- collider (Novosibirsk, Russia), as well as from the Japan Proton Accelerator Research Complex (J-PARC) at Tokai and other Japanese facilities such as LEPS @ SPring-8 and ELPH @ Tohoku. Furthermore, hadron structure investigations will profit enormously from an Electron-Ion Collider, which is under consideration in the US. Such a machine would allow for precision measurements over a large kinematical phase space with light polarised and heavy unpolarised ions.

JLab, Newport News, VA, United States

In the USA, Jefferson Lab is completing a major upgrade that involves doubling the accelerator energy to 12 GeV, upgrading the equipment of the existing experimental Halls and building the new Hall D. The latter hosts the GlueX experiment, which is designed to study meson spectroscopy in the light quark sector, making use of a high-intensity tagged photon beam and of a hermetic large acceptance detector. This will be complemented by the hadron spectroscopy programme carried out in Hall B with the CLAS12 detector that will use both quasi-real and virtual photon production to carry out an extensive programme in light quark meson and baryon spectroscopy. The new kinematic domain accessible by the increased beam energy will also allow for the multidimensional exploration of nucleon structure at increased values of momentum transfer. With its extremely high luminosity, JLab at 12 GeV will become a leading facility for accurate measurements of TMDs and GPDs in the coming years.

BESIII, Beijing, China

The Beijing Spectrometer (BES) is a general-purpose detector located in the interaction region at the BEPC storage ring, where the electron and positron beams collide with centre-of-mass energies ranging from 2 GeV to 4.6 GeV. The e^+e^- collider is part of the Institute of High Energy Physics, Beijing. BESIII features a very rich experimental programme with a very prominent series of hadron physics measurements, from hadron spectroscopy (light hadrons, charm and charmonium, both conventional and exotic) to hadron structure (electromagnetic form factors, fragmentation functions). The experiment is currently in the process of upgrading its central tracker and is expected to run into the first years of the next decade.

BELLE2, Tsukuba, Japan

Designed as a B factory, the BELLE detector has had an important impact in the discovery of new mesonic states. The KEKB e^+e^- collider which delivered beams to BELLE will soon be upgraded to the Super-KEKB accelerator, and a commensurate upgrade to the detector (BELLE 2) will be complete. There is a good chance that this facility will continue to yield important hadron spectroscopy results, in addition to its main objective of studying CP-violation.

RECOMMENDATIONS

Since the publication of the last Long Range Plan in 2010 enormous progress has been achieved, which presents clear evidence that Hadron Physics is a thriving field that has significantly extended our knowledge about the properties and interaction processes of hadrons. The availability of new experimental facilities, as well as progress in the theoretical treatment of hadronic systems has been of crucial importance. Some of the most important milestones concerning the experimental infrastructure include the successful upgrade of COMPASS and the completion of the 12 GeV upgrade at JLab. They are complemented by several accelerator facilities operated by universities, such as ELSA (Bonn) and MAMI (Mainz), with the MESA accelerator being on track for commissioning in 2020. GSI also contributes to the European research effort in hadron physics via the HADES experimental programme, which will continue to operate at FAIR.

The COMPASS experiment at CERN has made important contributions to hadron structure and spectroscopy, and data taking for the GPD run has started. At ELSA new baryonic states have been discovered while existing ones could be established more firmly. The spectroscopy programme of ELSA will continue performing polarisation experiments. A broad experimental programme on form factor measurements and spectroscopy is in place at MAMI. This will be extended further to allow for precision measurements of electromagnetic form factors, as well as parity-violating processes in scattering in the years after 2020. This also impacts on other fields such as atomic physics and tests of fundamental interactions.

Several important recent discoveries have firmly established that QCD predicts a much richer hadronic spectrum as would be expected from the quark model. The most spectacular examples include the observation of the Z_c particles at BESIII and the pentaquark at LHC-b.

Although the completion of the FAIR facility and the PANDA experiment have been delayed, they are eagerly awaited by the international community. It is important to note that the political decisions have now been taken which will secure the construction of FAIR and PANDA and the start of the physics programme within the next five years.

Against this backdrop we make the following recommendations:

First recommendation: Completion of the PANDA experiment at FAIR without further delays.

The strategic importance of PANDA for hadron physics cannot be underestimated. It provides a unique opportunity for a comprehensive research programme in hadron spectroscopy, hadron structure and hadronic interactions. The combination of PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world. Despite the delays in its construction, PANDA continues to be viewed as a major flagship experiment, which attracts a large international community.

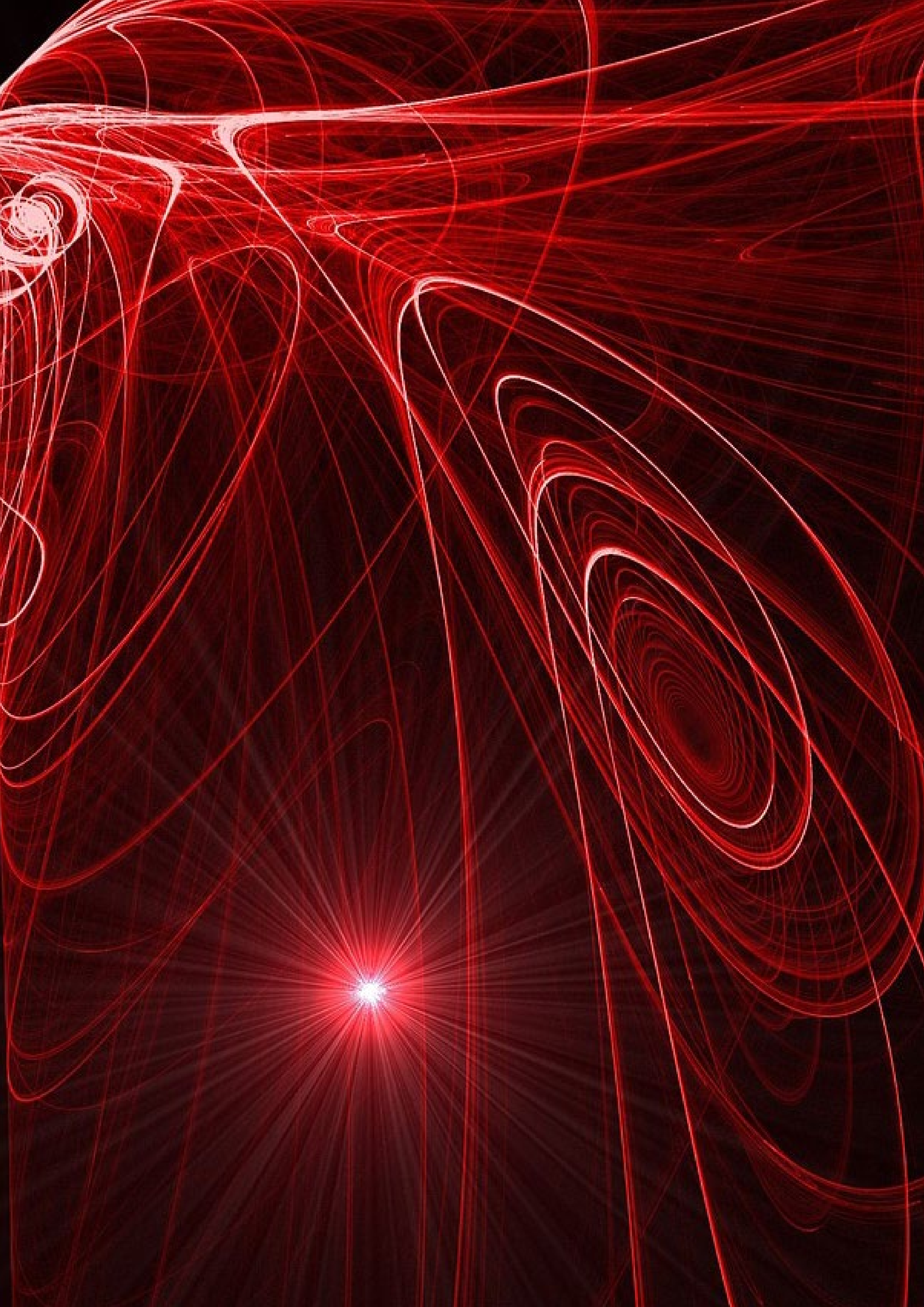
One of the key features of PANDA and the entire FAIR accelerator complex is the availability of an antiproton beam. Therefore, the completion and continued operation of the High Energy Storage Ring (HESR) is vital to sustain this unique research environment.

Second recommendation: Support for a research programme in precision physics at existing facilities

The currently operating facilities offer high-quality research programmes. Very significant new results can be expected not only from the big laboratories, such as CERN (LHC, COMPASS), GSI (HADES), JLab, IHEP and NICA, but also from smaller scale facilities, such as DAΦNE, ELSA, MAMI and, in the near future, MESA, where high-precision experiments can be performed. They will not only greatly advance our knowledge about hadrons and their underlying structures, but also explore the limits of the Standard Model. A quantitative understanding of hadronic effects with sufficient precision is necessary to detect signatures for physics beyond the SM. These facilities, whose scientific potential is complementary to FAIR, provide an ideal training environment for future generations of scientists and a highly qualified workforce.

Third recommendation: Support for theory and computing

Many of the major insights of recent years have been gained by confronting increasingly sophisticated theoretical tools with experimental data. The interplay between complementary theoretical approaches such as lattice QCD, effective field theories and functional methods has been a great asset for obtaining a deep understanding of hadronic properties in terms of fundamental interactions. Further progress depends crucially on the availability of large-scale computing facilities. We recommend that European computing laboratories receive the support that is necessary to provide an environment for internationally competitive calculations in lattice QCD.



2

PROPERTIES OF STRONGLY INTERACTING MATTER AT EXTREME CONDITIONS OF TEMPERATURE AND BARYON NUMBER DENSITY

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2. PROPERTIES OF STRONGLY INTERACTING MATTER AT EXTREME CONDITIONS OF TEMPERATURE AND BARYON NUMBER DENSITY

INTRODUCTION

Basics of QCD

Four fundamental forces rule the interactions of matter in Nature: the gravitational force, the electromagnetic force, the weak force and the strong force. Except for gravity, for which the quest of a microscopic quantum description has remained somewhat elusive so far, these forces are described in terms of local quantum field theories. In these theories, spin-1/2 matter fields carry charges pertaining to the local (gauge) symmetries of the theory and are coupled to spin-1 bosonic fields that mediate the interaction. For the weak and strong forces, these fields are also charged under the gauge symmetry.

The quantum field theory that describes the strong force, Quantum ChromoDynamics (QCD), has been formulated in the early 1970's, following a number of experimental clues. In particular, deep-inelastic scattering experiments led to two crucial observations: (i) the electrical charge of hadrons is not smoothly distributed but is carried by spin-1/2 constituents which, to the extent allowed by the spatial resolution of the experiments, are point-like, and (ii) these constituents are nearly free when probed at very short distances. QCD is the simplest field theory consistent with these properties and with the multiplets observed in hadron spectroscopy; it is a non-abelian gauge theory endowed with an internal local *SU(3)* symmetry, in which the charged matter fields are referred to as *quarks* and the mediators of the force as the *gluons*.

Although there are six flavours of quarks (up, down, strange, charm, beauty and top), only the lightest two (up and down) appear in the valence composition of nucleons. The heavy quark flavours may appear as short-lived quark-antiquark quantum fluctuations in the hadronic wavefunctions and may also be produced in the final state of various reactions.

Two important properties of QCD are *asymptotic freedom* and *colour confinement*: the strength of its coupling decreases at short distance and increases at large distance (in contrast to Quantum Electrodynamics, where the coupling evolves in the opposite way). This behaviour explains both the scaling observed in deep-inelastic scattering experiments and the fact that the force becomes strong enough at larger distance to bind the quarks into hadrons. Neither quarks nor gluons exist as isolated particles in Nature, and the only stable arrangements are colour-singlet bound states, i.e., hadrons, which may either be mesons formed from quarks and antiquarks or (anti)baryons formed from three (anti-)quarks. Also more exotic states, e.g. made purely from gluons (so-called glueballs) or from more than three quarks, have been suggested to exist. For instance, it is believed that tetraquark states have been produced in several experiments. Pentaquarks states have been much more elusive so far, but may have been seen in the products of proton-proton collisions at the LHC. However, despite the fact that confinement prevents a direct observation of quarks and gluons, they leave clear imprints in high-energy reactions in the form of *jets* - collimated streams of hadrons whose direction reflect the momentum of the quark or gluon that initiated them.

Asymptotic freedom has a very profound implication for hadronic matter under extreme conditions: at sufficiently high nuclear density or temperature, the average inter-parton distance becomes small, and therefore their interaction strength weakens. Above a critical energy density of the order of 0.3 GeV/fm^3, a gas of hadrons undergoes a deconfinement transition and becomes a system of unbounded quarks and gluons called quark-gluon plasma (QGP). Numerical evidence of this transition has been obtained from lattice simulations of QCD, in the form of a rapid increase of the entropy density around the critical energy density. The deconfinement of quarks and gluons is accompanied by a restoration of chiral symmetry, spontaneously broken in the QCD vacuum.

In the cooling history of the Early Universe, the primordial QGP turned into hadrons around a few microseconds after the Big Bang, but this transition has, as far as we know, not left any imprint that is visible in present-day astronomical observations. However, the energy density necessary to form the QGP may be re-created in the laboratory via heavy-ion collisions at sufficiently high energies, within volumes of the order of the nuclear size.

QCD phase diagram

In equilibrium, the phase structure of nuclear matter is controlled by a small number of local thermodynamical parameters: the temperature T and the chemical potentials associated to conserved quantities, the most important of which is the baryon chemical potential, μ_B, related to baryon number conservation. Figure 1 summarizes our present knowledge of the phase diagram in the temperature T, chemical potential μ_B plane. More specifically:

a) In the chiral limit of two-flavour QCD, i.e., for vanishing up- and down-quark masses, a phase transition exists, that separates a phase of broken chiral symmetry at low temperature from a chirally symmetric phase at high temperature. This transition also persists at small, non-vanishing values of the baryon chemical potential.

b) For QCD with its physical spectrum of small but non-zero up and down quark masses and a heavier strange quark, the transition from the low- to the high-temperature regime is rapid and accompanied by large changes in the properties of strongly interacting matter. However, it is presumably not a genuine phase transition but a ''cross-over transition''. At vanishing baryon chemical potential this transition occurs at about k_BT = 155 MeV and restores chiral symmetry up to residual explicit breaking effects arising from non-zero values of the light quark masses. It also shows clear features of a deconfining transition, with the low-temperature regime being best described by ordinary hadronic degrees of freedom, while in the high-temperature phase quarks and gluons emerge as the dominant degrees of freedom.

c) Properties of strongly interacting matter at very high temperature or baryon chemical potential can be calculated using perturbative techniques. In this asymptotic regime, nuclear matter consists of weakly interacting quarks and gluons in the QGP phase. At least for high temperatures and vanishing baryon chemical potentials such calculations can be cross-checked with lattice-QCD calculations.

d) Close to the cross-over region, in particular on the high-temperature side of the transition, nuclear matter is strongly coupled. In this region, the transport coefficients are very small, implying a strong collective behaviour of the nuclear matter. This has profound consequences on our understanding of heavy-ion collisions: despite large space-time gradients in these collisions, strongly interacting matter exhibits properties similar to those of an ideal fluid.

e) One or more colour-superconducting phases exist at asymptotically large net baryon number density and sufficiently low temperature. It is rather likely that this phase is homogeneous, but it may display spatial variations of the colour-superconducting order parameter when the density is lowered.

f) Under conditions of vanishing pressure and temperature nuclear matter forms a quantum Fermi liquid with a density of about 0.16 nucleons per fm^3. Upon heating, it undergoes a first-order liquid-gas transition, which ends in a critical point of second order. The associated critical temperature is rather well established to be around 15 MeV.

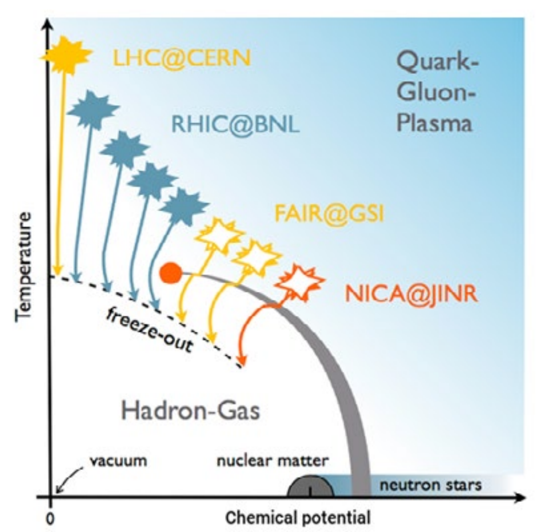
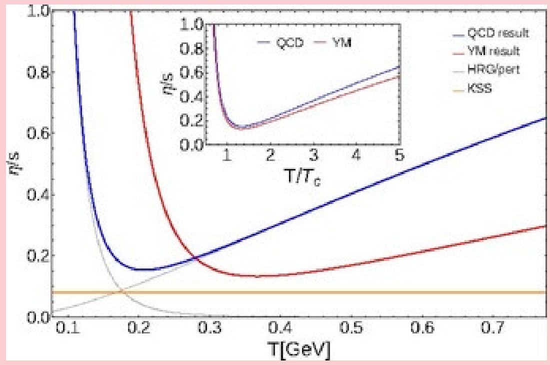


Figure 1: Illustration of the QCD phase diagram. Adapted from J. Phys. Conf. Ser. 432 (2013) 012013, courtesy of C Schmidt.

Apart from these few anchor points, our knowledge of the phase diagram from first-principle approaches remains scarce, in particular in the experimentally interesting region of intermediate net baryon number densities. At present, these regions are not accessible to lattice-QCD calculations. In order to shed light on their properties, phenomenological studies have been performed, using models that have some resemblance to QCD while avoiding its technical problems. To give one example, in QCD with a large number of colours, a new phase, termed the "quarkyonic phase", was proposed at low temperatures and baryon chemical potentials exceeding that of the nuclear matter ground state. However, without experimental constraints, these model approaches often lead to inconclusive results.

Box 1

Theoretical tools for calculating the EoS and transport coefficients At high temperatures or high chemical potentials, asymptotic freedom allows computing the partition function perturbatively in terms of a power series in the strong coupling constant, provided one resums the large corrections due to collective effects (e.g. Debye screening, Landau damping...).



FRG calculation of the shear viscosity to entropy ratio as a function of temperature (from Phys. Rev. Lett. 115 (2015) no.11, 112002)

As one decreases temperature and chemical potential towards values of the order of the QCD scale parameter, O(GeV), weak coupling techniques are no longer applicable. A non-perturbative first-principle approach is lattice QCD. Calculations with physical quark masses are computationally expensive, but advances in computing hardware and algorithms have rendered them feasible.

This method works very well only for vanishing baryon chemical potential. At non-zero μ_B, the fermionic determinant contained in the integrand becomes complex valued, precluding Monte-Carlo samplings. At small baryonic chemical potential ($\mu_B/T \lesssim 1$), other methods (reweighting, Taylor expansion, analytic continuation of calculations performed at imaginary μ_B) may be used to partially circumvent this problem.

When applied to the calculation of transport coefficients, lattice QCD faces an additional difficulty related to the extraction of a spectral function from a Euclidean correlator, which requires some prior information about the unknown spectral function. A common approach is the Maximal Entropy Method (MEM), a Bayesian method to obtain the most likely spectral function.

Besides lattice QCD, other non-perturbative first-principle methods are functional methods in the continuum, such as Dyson-Schwinger equations (DSEs) or the Functional Renormalization Group (FRG), that do not suffer from the fermion sign problem and can thus be applied at any value of T and μ_B. Although a priori exact, these approaches require truncations in practice, which makes them approximate.

Equation of state, thermodynamics and transport

The equation of state (EoS) and other thermodynamical properties of a system in equilibrium are encoded in its partition function, while its transport coefficients can be extracted from the low momentum behaviour of spectral functions.

In regions of high temperature and/or high baryon chemical potential, a perturbative approach is possible thanks to asymptotic freedom. In regions where the coupling constant is large, non-perturbative calculations are necessary. In the strip where $\mu_B/T \ll 1$, one may use lattice QCD. However, lattice QCD fails at large μ_B due to a ``sign problem'': the integrand is not positive definite and thus cannot be sampled by a Monte-Carlo method. Various analytical methods have been developed to circumvent this problem, but they all involve truncations and are therefore approximate. More details on these techniques can be found in Box 1.

Heavy-ion collisions

The idea to collide heavy ions accelerated at ultra-relativistic energies for bringing nuclear matter into the deconfined QGP phase and studying its properties in the laboratory dates back to the early '80s (see the Box 2 for a timeline of heavy-ion facilities). Pioneering studies promptly demonstrated that the energy deposit and the nuclear stopping in the central rapidity region were quite large. The acceleration of truly heavy ions at the SPS, since 1994, and the accompanying experimental programme with 2nd or 3rd generation experiments allowed researchers to determine the properties of a system with energy density above the critical value and to observe several of the predicted signatures of the QGP. At higher center-of-mass energy, the colliding system enters a new regime characterized by nuclear transparency: the inertia of the colliding nucleons becomes so large that they cannot be completely stopped. Nevertheless, the initial energy density in the central rapidity region, inferred from the number of produced particles via the Bjorken's formula, keeps increasing with energy. The net baryon density at mid rapidity approaches zero already at the BNL Relativistic Heavy Ion Collider (RHIC) energy ($\sqrt{s_{NN}}$ = 200 GeV), and the initial energy density in central PbPb collisions at the Large Hadron Collider (LHC) at CERN

($\sqrt{s_{NN}}$ = 2.76 TeV) is more than an order of magnitude larger than that of the deconfinement transition predicted by lattice QCD. The challenge for the coming years consists in a detailed experimental characterization of the different features of the phase diagram (e.g. the critical endpoint) as well as a determination of the parameters that characterize the hot medium (e.g. its transport coefficients). In this quest, the experimental control variables are the colliding energy, the ions used in the collisions and the centrality of the collisions.

HIGH-TEMPERATURE MATTER

In this Section, we focus on the strongly interacting QGP (sQGP) produced in nuclear collisions at the highest available energies. In these collisions, the QGP is formed with high temperature and low baryon chemical potential μ_B, i.e., with a minimal excess of quarks over anti-quarks. The QGP produced in these collisions is therefore very similar to the QGP in the early Universe and is in the low μ_B limit where lattice QCD calculations are reliable.

The goal of the high-energy heavy-ion programme is to identify and characterize the properties of the QGP. This programme naturally has two steps: understanding the dynamics of heavy-ion collisions, e.g., via comparison to phenomenological models, and the extraction of fundamental QGP/QCD properties that can be compared to (lattice) QCD results.

Figure 2 illustrates the three main stages of a heavy-ion collision: (i) an early non-equilibrium stage, (ii) an expansion stage, and (iii) a final freeze-out stage. An advantage of this modular structure is that it allows for the use of more or less advanced theoretical tools in each stage. In this way the modeling of heavy-ion collisions can be gradually improved and used to constrain further the properties of strongly interacting matter. This picture, and the associated phenomenology, has indubitably evolved over the last 30 years as observables have been identified that are sensitive to specific processes in each phase.

The first stage, which also provides initial conditions (spatial distribution of the deposited energy and pressure, initial flow velocity) for the subsequent hydrodynamical stage, is the least known and is often described by simple geometrical models (e.g. the Glauber Monte-Carlo approach) in which the underlying strong interactions are encapsulated in the inelastic nucleon-nucleon cross-section. More ab-initio descriptions, such as the Colour Glass Condensate (CGC), in which one treats the collision in terms

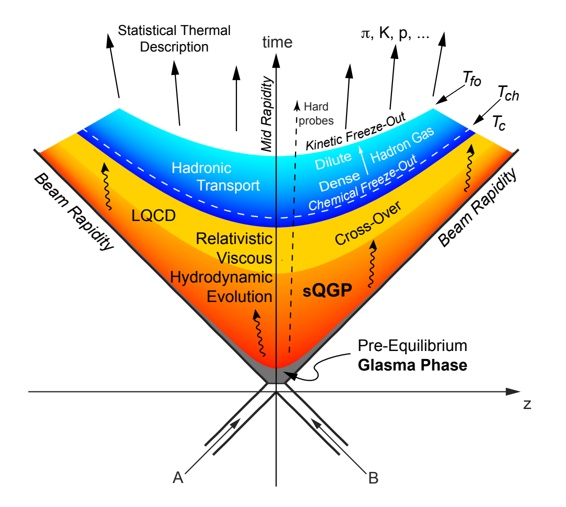


Figure 2: Space-time evolution of the system created in heavy-ion collisions. The different stages are specified on the right side and some theoretical tools used to describe them are listed on the left side.

of partonic degrees of freedom (mostly gluons in the relevant kinematical regime for RHIC and the LHC) and the QCD interactions, are being actively developed nowadays. Although some observables that have been measured by LHC experiments in PbPb collisions (e.g. *J/ψ* photo-production) provide evidence for nuclear gluon shadowing, further efforts are required to extract its amount. A more comprehensive study of this regime of large nuclear gluon density will be possible at the Electron-Ion Collider (EIC) currently planned in the USA, by allowing a direct measurement of nucleonic and nuclear structure functions, and in particular the longitudinal one which is most directly sensitive to the gluon content. In the CGC picture, the initial scatterings produce a dense system (made of strong colour fields, the so-called Glasma) that quickly approaches a hydrodynamical regime. It takes less than one fm/c for the system to become a nearly perfect fluid whose expansion can be described by relativistic viscous hydrodynamics.

During the second stage –the fireball expansion–, the bulk evolution is described by relativistic viscous hydrodynamics. Due to the near perfect fluid nature of the QGP, the initial geometrical anisotropy is efficiently converted into a momentum anisotropy of the final particles. Event-by-event fluctuations lead in the final state to significant higher order harmonics (triangular flow and above) of the azimuthal particle distribution, in addition to the 2nd order one (elliptic flow). Their systematic measurement has recently provided an avenue for constraining initial-state model calculations and transport properties of the QGP both at RHIC and the LHC. Moreover, this bulk evolution provides the substrate for the medium modifications of hard probes, although a better integration of these two aspects of the description is certainly needed.

Hadronisation takes place when the system reaches the pseudo-critical temperature (in the hydro-dynamical description, this transition is encoded in the EoS). After hadronisation, the scattering rate decreases quickly and a kinetic description becomes more appropriate than hydrodynamics. This third stage may be described by hadron cascade models such as, e.g. UrQMD. Given the cross-sections for the scatterings between the various hadrons species, this kinetic description can in principle describe the (possibly successive) decoupling of the hadrons from the fireball. The measured relative abundances of hadrons indicate that chemical freezeout happens at a temperature T_{ch} which is very close to the hadronisation temperature and at nearly zero μ_B. Subsequently, the hadrons continue to rescatter elastically until they reach the kinetic freeze-out temperature, T_{fo}, where they decouple and freely stream to the detectors.

Since the last NuPECC long range plan, the LHC has started and completed its first heavy-ion running period, 2010-2013, and begun its second period, 2015-2018. The LHC data extend the rich experimental programmes at the Bevatron, SPS and RHIC, increasing by factors of about 7, 25 and 55 the energies accessible in proton-proton, heavy-ion and proton-ion collisions, respectively. This jump in collision energy has provided abundant access to so-called hard probes, whose production is calculable within perturbative QCD and any modification due to the propagation through the medium can be used to probe the QGP properties. At the LHC, the energy loss of heavy charm and beauty quarks can be directly compared for the first time, which allows testing the quark mass dependence of the energy-loss mechanisms. The much more abundant charm production greatly increases the J/ψ production rate by coalescence of c and c quarks. The J/ψ yield in PbPb collisions at the LHC is consistent with deconfinement followed by such a recombination. For Υ states, the much larger production cross-section has enabled the first measurement of the dissociation of the 1S, 2S, and 3S bound states individually

In addition to the rich new set of heavy-ion results from the LHC, unexpected novel insights related to initial state dynamics has come from pp and pPb collisions. It was expected that these collisions would mainly provide a calibration of the initial state and it was therefore surprising to observe large azimuthal anisotropies of the underlying event in these systems. These asymmetries are very similar to those seen in heavy-ion collisions, where they are attributed to the creation of the sQGP perfect fluid.

The LHC has run pPb collisions again in 2016, due to the large interest in small systems, and it is expected that in 2018 there will be a long PbPb run. In 2019-2020, the LHC will be shut down to upgrade and prepare the experiments for Run-3. The goal of the heavy-ion upgrades is to be able to handle optimally the factor ~10 increase of the event rate to 50 kHz. In the case of the ALICE detector, which is the only dedicated heavy-ion experiment at the LHC, the upgraded detector will be able to analyze the full rate of events online, thereby increasing the sensitivity for most measurements by one to two orders of magnitude.

Box 2

Timeline of former and current heavy-ion facilities

Bevatron (Billions of eV Synchrotron): from 1954 to 1993 at Lawrence Berkeley National Laboratory, U.S.

AGS (Alternating Gradient Synchrotron): since 1960 at Brookhaven National Laboratory, U.S. It is now used as injector for RHIC.

SPS (Super Proton Synchrotron): since 1976 at CERN, Switzerland. It is now the injector for the LHC.

SIS-18 (SchwerIonenSynchrotron): since 1990 at GSI, Germany.

RHIC (Relativistic Heavy Ion Collider): since 2000 at Brookhaven National Laboratory, U.S.

LHC (Large Hadron Collider): since 2009 at CERN.

Recent Experimental and Theoretical Developments

One of the long-standing puzzles in the field is the question of how the colliding system evolves quickly towards a local isotropic state in momentum space. Two important developments were made recently towards solving this 'fast isotropization' puzzle. On the one hand, descriptions of the initial state based on CGC initial conditions have shown that the approach to isotropy in such dense systems is much faster than in the hard-scattering regime. On the other hand, developments within relativistic viscous hydrodynamics have shown that significant deviations from isotropy can be realized even with a small viscosity. These developments offer the perspective of describing via viscous hydrodynamics the full evolution from the initial saturated gluon state to the final freeze-out stage, in an almost seamless fashion.

Unlike hadronic observables, whose prediction is complicated by final state interactions, photons and di-leptons interact only electromagnetically and therefore escape from the fireball without re-interacting after production The yield of thermal photons (i.e. the black body radiation from the hot QGP) is very sensitive to the QGP temperature and can be predicted by a combination of QCD perturbative calculations and hydrodynamical simulations. Direct photons have been measured in PbPb collisions at the LHC ($\sqrt{s_{NN}}$ = 2.76 TeV). At low p_T, one observes an excess over the non-thermal photons (prompt photons from collisions of the quarks and antiquarks contained in the incoming nuclei, photons from meson decays, etc.) that agrees reasonably well with model predictions of thermal photons (with an initial QGP temperature around k_BT = 400 MeV at a time τ_0 = 0.4 fm/c for central collisions).

One of the most important discoveries of the heavy-ion programme is that matter produced in heavy-ion collisions behaves as a nearly perfect (not viscous) fluid. This conclusion was already reached based on RHIC data, and the LHC has shown that it also holds for systems with higher initial temperature. Figure 3 shows the relevant experimental results of the second-order harmonic anisotropy v_2 (elliptic flow) as a function of p_T, for different particles. The results are compatible with calculations of relativistic fluid dynamics (hydrodynamics) in which the fluid has a very low viscosity. Deviations from an ideal fluid may be quantified by the shear-viscosity-to-entropy-density ratio η/s. This ratio is estimated by comparing hydrodynamical calculations to the measurements in Figure 3, leading to a value in the range $1 < \eta/s < 2.5$ in units of $\hbar/(4\pi k_B)$.

This value is smaller than that of any other known substance, including superfluid liquid helium, and is very close to the value $\eta/s = \hbar/(4\pi k_B)$ obtained in some exactly solvable field theories in the limit of infinite coupling, suggesting that the QGP is also a strongly interacting medium. Recently, it has been demonstrated that the inclusion of bulk viscosity effects in event-by-event simulations can have an impact on both the flow harmonics and particle spectra. This offers exciting prospects for determining the bulk viscosity to entropy ratio, ζ/s, from experimental data.

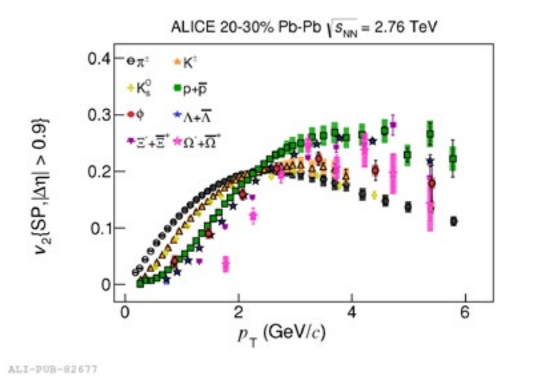


Figure 3: Elliptic flow coefficient as a function of transverse momentum, for various hadron species. From JHEP 06 (2015) 190.

The important question of the thermalisation of heavy quarks appears to be partly answered for charm: the positive elliptic flow of charmed hadrons indicates that charm quarks take part in the collective expansion of the QGP. Their degree of thermalisation is however not well constrained. For the beauty sector, thermalisation remains an open issue.

Analyses of the ratios of hadronic yields within statistical hadronisation models (SHM) indicate a temperature of chemical freeze-out just below the hadronisation temperature, and almost zero baryon chemical potential. Nowadays, these models also include, besides the ratios, fluctuations of conserved charges inferred from susceptibilities computed in lattice QCD simulations.

For the high temperature and low μ_B values extracted at the LHC, the yields of matter and anti-matter are almost equal (they differ only by the baryon number of the incoming nuclei, that remains localized at forward rapidities). These collisions are therefore the most abundant source of anti-nuclei in the laboratory. This makes it possible to compare the properties of nuclei and anti-nuclei in order to look for CPT violating effects.

This has recently been done in a measurement by ALICE of the mass of anti-nuclei up to anti-deuterons and ^{3}He. Within the achieved experimental uncertainties, no difference was observed, so that this measurement provides the most stringent constraint on CPT violation in the strong interaction at distance scales above 1 fm. It is also remarkable that the yield of these weakly bound objects is perfectly compatible with the SHM predictions, suggesting they are in chemical equilibrium. With the statistics expected in upcoming LHC runs, a similar measurement may be possible for ^{4}He.

Basic space-time properties of the fireball can be inferred from Hanbury Brown–Twiss (HBT) interferometry analyses. The volume of the system at freeze-out is found to increase linearly with the charged particle rapidity density at RHIC and the LHC. The largest volume at the

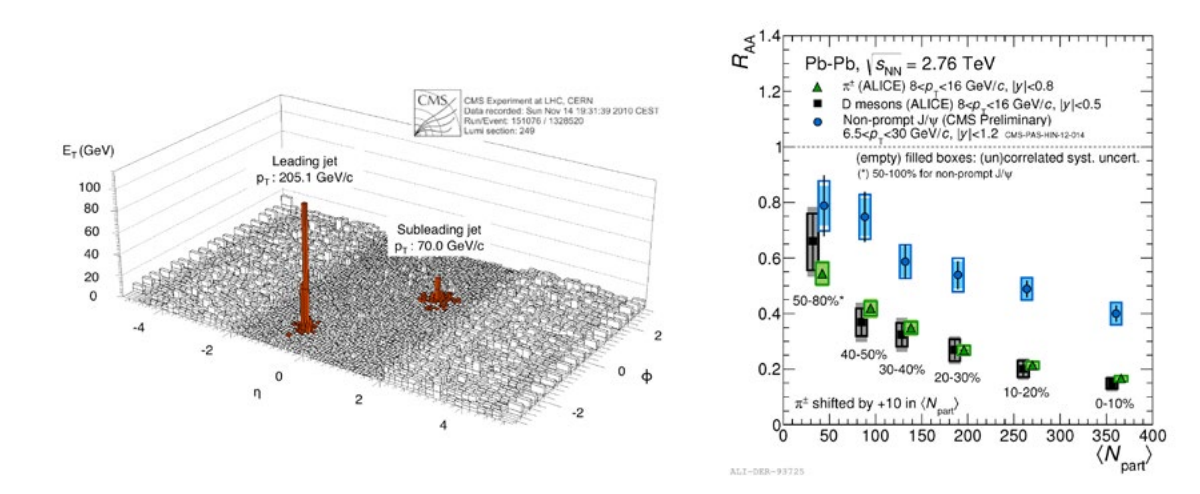


Figure 4: The left panel shows the transverse energy E_T distribution in a single event as a function of the azimuthal angle φ and the pseudorapidity η (from Phys. Rev. C84 (2011) 024906.). The large imbalance in transverse energy of the two jets (marked in red) indicates that at least one of the partons has lost significant energy in the quark-gluon plasma. The right panel shows the event-averaged nuclear modification factor R_{AA} for light hadrons $\pi^{\pm}$, heavier *D* charm mesons, and non-prompt *J/ψ* from beauty quark decays (from JHEP 1511 (2015) 205 and JHEP 1205 (2012) 063). The suppression (R_{AA} < 1) is stronger for more central collisions (larger $\langle N_{part} \rangle$) and the particle species differences are as expected from the quark-mass dependence of the energy loss.

LHC ($\sqrt{s_{NN}}$ = 2.76 TeV) is approximately 4800 fm^3, about twice the volume obtained from a similar analysis at top RHIC energy. This volume corresponds to a radius of 10 fm which is close to the one extracted phenomenologically from SHM analyses of the hadron abundances. The HBT analysis also provides information about the duration of the longitudinal expansion of the system. The estimated time until freeze-out at the LHC is about 10 fm/c, which is 30% larger than the value obtained at RHIC.

Two important recent measurements of parton energy loss at the LHC are shown in Figure 4. The left panel, from the CMS experiment, shows an event display of a dijet event in a heavy-ion collision: the red towers in the figure indicate 'jets', i.e., regions with large transverse energy flow, which are remnants of high-energy quarks or gluons. Without a dense medium, QCD at leading order predicts that the two jets have equal p_T's (unbalanced p_T's come from higher order corrections). The observed imbalance therefore indicates that (at least) the lowest energy jet has lost a large amount of energy. The emerging picture from jet measurements at the LHC is that the particle distribution inside quenched jets appears to be roughly similar to that in unquenched jets of the same reconstructed energy and that the lost energy is recovered in the form of low momentum particles at large angles (above 0.5 radians). Moreover, there is no complete theoretical understanding of how the large-angle transport comes about, although various theoretical ideas have been proposed, most notably 'anti-angular ordering' and 'democratic branching', which pave the way to a better understanding of these observations. These topics will form the core programme of future research on parton energy loss and jet quenching at the LHC.

Energy loss can be further quantified via the momentum dependence of the nuclear modification factor R_{AA}, the ratio of an invariant yield obtained in heavy-ion collisions to an incoherent superposition of the same yield in nucleon-nucleon collisions. Parton energy loss manifests itself by lower-than-unity values of this ratio, at high momentum. The measured nuclear modification factors at the LHC are summarised in the right panel of Figure 4. A large suppression is observed in central PbPb collisions, where the plasma is larger and hotter. Furthermore, there is a difference between R_{AA} for light hadrons ($\pi^{\pm}$), *D* mesons (which contain a charm quark) and non-prompt *J/ψ* from heavy *B* mesons (which contain a beauty quark) decays. This difference is in line with theoretical models that include interference effects that depend on the velocity, and hence on the mass, of the propagating particles.

An important aspect of the parton-medium interaction is the path-length dependence of the parton energy loss. Different energy loss mechanisms have different characteristic path-length dependences: collisional energy loss would give a linear dependence, while radiative loss gives a quadratic dependence (at lowest order) due to quantum-mechanical interference effects in the regime probed in heavy-ion collisions. Even stronger path-length dependences have been obtained in the strong coupling limit and QCD synchrotron radiation. Several measurements have been made to explore the path-length dependence of energy loss, most notably using dijets (and dihadrons) or the azimuthal anisotropy of jet quenching. However, extracting the path-length dependence of the energy loss requires both a dynamical understanding of the medium density evolution and detailed modeling of the parton-medium interactions. The first aspect is closely related to the emerging global description of the system, while the second is a topic of active theoretical developments. A general trend is that jet quenching studies lead to somewhat larger initial energy densities than those required for the hydrodynamical description of the flow measurements. More precise differential measurements and further developments of the jet quenching theory are needed in order to understand the matching between the descriptions of the soft and hard sectors.

Quarkonia, which are rare bound states of a heavy flavour (charm or beauty) quark and anti-quark, are particularly important hard probes, because the QGP medium is expected to dissolve these bound states leading to an observable suppression. Each charmonium and bottomonium state has a different binding energy and one expects a gradual melting of the more tightly bound states (from less to more bound) as the plasma temperature increases. The in-medium dissociation rates of these states are therefore expected to provide an estimate of the initial (see Figure 5) temperature reached in the collisions. The LHC data have demonstrated such thermal effects for bottomonia, which seem to exhibit a sequential suppression pattern of the 1S, 2S, and 3S states.

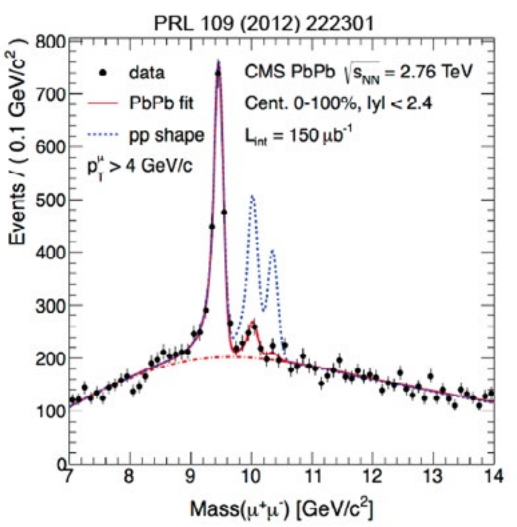


Figure 5: Yield of di-muons in the invariant mass region of the Upsilon states. Points: LHC data in PbPb collisions. Solid line: PbPb fit. Dotted line: rescaled pp invariant mass spectrum. From Phys. Rev. Lett. 109 (2012) 222301.

At the LHC, where a large number of charm quarks are produced in each nucleus-nucleus collision, one measures a sizeable increase of *J/ψ* at low p_T relative to the suppression at higher p_T, and a lower overall suppression than at RHIC. This is compatible with a strong thermal dissociation of charmonia, followed by recombination of charm and anti-charm quarks produced initially in two separate hard scatterings. Whether production takes place throughout the full – or most of the – lifetime of the deconfined state or rather suddenly at the confinement cross-over cannot be disentangled using the existing measurements, but requires a larger set of measurements, including additional quarkonium states.

Collisions of small systems, such as proton-proton, proton-nucleus, deuteron-nucleus, as well as helium-nucleus, have for long been thought to be dominated mainly by initial state effects rather than by final state interactions. Nevertheless, the multiplicity measured in pPb collisions at √sNN = 5.02 TeV is comparable to that produced in peripheral PbPb collisions at √sNN = 2.76 TeV, suggesting a similar deposited energy for a comparable number of participating nucleons. In addition, flow measurements for these collisions of small systems have shown significant multiparticle correlations in the final state. Moreover, very recently ALICE has observed an enhanced production of strange particles in a subset of p-p collisions characterized by a large particle multiplicity. These results for small systems are intriguing and various theoretical explanations have been proposed, ranging from the hydrodynamical expansion of a proton-sized droplet of fluid to correlations inherited from the wave-functions of the incoming projectiles in a CGC description. These theoretical studies should be continued and developed, accompanied by an active programme of measurements to further explore the similarities and differences between PbPb and pPb collisions, in order to better understand the nature of the space time dynamics of high-energy collisions. Another dimension to study these phenomena would be to explore various combinations of projectiles and geometries, something that could be achieved with a second ion source at CERN.

Future Plans and Expected Developments

The research programme for the properties of the Quark Gluon Plasma at high T and low μ_B concentrates on nuclear collisions at the largest available energies, which provide the hottest, densest, and longest lived QGP. The experimental programme is therefore aiming at the full exploitation of the high-energy collisions delivered by the LHC. The most important open questions that will be addressed in the coming years are in four different areas, namely thermalisation/isotropisation at early times, jet modification and energy flow (including flavour dependence), the interplay of hot and cold matter effects in quarkonium production and absorption, and finally the use of electromagnetic observables to probe the initial state temperature and possibly get insight in the mechanism for chiral symmetry breaking. Progress in each of these areas relies on larger data samples for more precise and differential measurements, as well as a continuous dialogue between experimental results and theoretical developments.

As discussed earlier, we now understand the early time development of the collision much better than at the time of the previous Long Range Plan: it is clear that dense gluon field dynamics drives the system towards isotropy much faster than initially thought and that viscous fluid dynamics can accommodate the residual anisotropy. The dense gluon fields in the nucleus may be probed by measurements of forward particle production, which are being performed by LHCb and the forward muon arm of ALICE. In the 2016 pPb run, the LHC has operated at a higher energy and therefore probed larger gluon densities. ALICE is also studying a possible future upgrade with a forward calorimeter, to measure direct photon production, which would provide a direct measure of the gluon density in the nucleus in a new regime.

The discovery of collective effects in pp and pPb collisions poses an important new question: what is the minimum system size or density that can produce flow? This question is the subject of active theoretical work. Experimentally, this will be further explored using pPb collision data recorded during the 2016 run and new analysis techniques that are under development. This programme is expected to lead to an understanding of QCD dynamics that encompasses small and large systems.

In heavy-ion collisions, heavy quarks provide a promising probe of thermalisation, since they are produced early in the collision and then interact with the flowing medium. First results are available, but the large data samples of LHC Run-2 (2015-2018), Run-3 (starting in 2021) and Run-4 are needed in order to achieve the precision required to discriminate different scenarios. The ALICE detector will be upgraded to improve the measurement of heavy flavour flow at low p_T, a very sensitive probe of thermalisation.

New observables are being explored to improve the determination of QGP properties. In particular event-plane correlations, flow fluctuations and correlations between harmonic coefficients have been shown to be sensitive to the bulk viscosity. In the coming years, the bulk viscosity to entropy ratio, ζ/s, may be estimated from experimental data, so that the two main viscosity coefficients of QGP can be determined. In the future, the shear and bulk viscosities might be found directly from QCD and one will use these values in the hydrodynamic calculations in order to check the overall consistency of the theoretical frameworks.

The high energy of the LHC has opened up a new area of research, using fully reconstructed jets to probe the properties of the QGP. The results from the first LHC run clearly show a large energy loss, but also pose new questions, in particular about the mechanism for energy redistribution to large angles. The cleanest probe of this process would be to measure events with a hard jet and a hard photon (or Z boson) whose energy is measured and serves as a reference for the initial jet energy. Proof-of-principle measurements of this type have been performed already, but the large data samples of Run-2, Run-3 and Run-4 are needed to provide a quantitative measure of the energy redistribution in these events and consequently discriminate scenarios for parton energy loss in the QGP. In parallel, theoretical tools to calculate multiple parton emissions in QCD are being developed.

In the area of quarkonia, several effects are expected to play a role, including the melting of quarkonia in the QGP, cold nuclear matter effects, such as hadronic co-movers and initial state energy loss, and the recombination of heavy quarks into quarkonia. Future measurements of the excited charmonium states, as well as higher precision measurements of the bottomonium states in pPb and PbPb collisions will help to disentangle these effects.

Direct photon and di-lepton measurements provide the cleanest probes of early dynamics, including thermal radiation and potential signals of the chiral phase transition through in-medium spectral functions of the ρ and other vector mesons. These measurements are extremely challenging and require large data samples and low background (photon conversion) conditions, with no possibility to perform on-line selections of the collisions. Measuring di-leptons to identify thermal radiation is one of the most challenging goals of the ALICE ongoing upgrades for the run period after 2020.

The interest in this field and the opportunities at the LHC are clearly illustrated by the growing community of high-energy nuclear physicists: the European community of heavy-ion physicists, which was initially almost exclusively involved in ALICE, includes at present sizeable groups in both CMS and ATLAS experiments, as well as a starting activity within LHCb. In the coming years, a number of detector upgrades are planned (see Section 4) and the LHC will provide larger collision energies at higher interaction rates. This may allow exploring the temperature and density dependence of the basic properties of hot QCD matter, and refining the hard probe measurements so that they become quantitative tools. An active programme on collective effects in small systems is also under development. We consider it crucial that all these aspects of the LHC programme, including the detector upgrades, are well supported in the coming years.

HIGH-DENSITY MATTER

In parallel to the study of high-temperature QCD matter as described in the preceding section, the interest in nuclear collisions at lower energies has grown substantially over the past decade and has led to a number of experimental programmes at existing facilities and even to new accelerator facilities now under construction. The goal of these programmes is to explore the structure of the QCD phase diagram at non-vanishing baryon chemical potential μ_B.

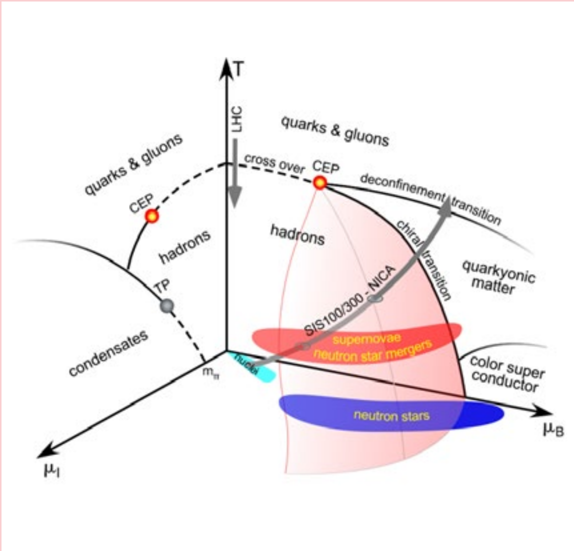
At moderate collision energies, baryon number is transported from the colliding nuclei to the mid-rapidity region, thus creating there a medium with finite net-baryon density. The study of the hadron yields at chemical freeze-out as well as transport models indicate that the net-baryon density (or, equivalently, the baryon chemical potential μ_B) increases with decreasing beam energy, with a maximum around 30A GeV, where a density of up to ten times that of the nuclear ground state is reached, i.e., a density which we believe it exists in the cores of neutron stars. The corresponding part of the phase diagram can presently not be addressed theoretically by first-principle calculations like lattice QCD. QCD-inspired effective models, however, suggest a rich structure as illustrated in Box 3. Its features are a first-order phase transition to deconfined matter, which is separated from the cross-over region at low μ_B by a critical point. Moreover, at large μ_B, the restoration of chiral symmetry could fall apart from the transition to deconfined matter, giving rise to a confined phase with partially restored chiral symmetry. This "Quarkyonic" matter appears in the QCD limit of a large number of colours and can be described as a Fermi gas of confined quarks with baryonic excitations. At very high μ_B and low temperature, it is expected that condensation of quark pairs takes place, leading to the phenomenon of colour super-conductivity. This gives rise to a rich phase structure in that region, depending on the various flavour-colour symmetry structures.

Considering also non flavour-symmetric matter opens additional dimensions to the QCD phase diagram. As an example, hyper-matter (with non-zero strangeness content) in form of single or double hyper-nuclei, where one or several nucleons are replaced by a hyperon, or in form of other multi-strange metastable objects (MEMOS) can be studied in nuclear collisions. Model calculations indicate that the most promising energy range is 5A -10 AGeV. This includes also the clarification of controversial issues like the existence of anti-kaonic nuclear bound states.

Beyond its importance for the understanding of fundamental properties of QCD, the study of high-density matter is also of high interest in the context of astrophysics. The recent discovery of neutron stars with masses of about two solar masses imposes severe constraints on the nuclear EoS, since the appearance of hyperons softens the EoS to an extent that such heavy neutron stars may collapse into black holes. Heavy-ion collisions at moderate energies produce baryon densities similar to those in the core of neutron stars ($\rho/\rho_0 > 5$), albeit at higher temperature and with different net-isospin. They should thus allow the extraction of features of the EOS, which are relevant for the understanding of the stability of neutron stars. Their study hence complements the direct observation of neutron star radii with improved resolution.

EXPERIMENTAL HANDLES FOR THE EXPLORATION OF THE QCD PHASE DIAGRAM

The detection of the landmarks of the phase diagram of strongly interacting matter at large net-baryon densities (e.g., first-order phase transition, critical point) would constitute a breakthrough in our understanding of QCD. There is, however, little quantitative guidance from theory as to the location of these landmarks in the phase diagram. The general experimental strategy is thus to scan



Box 3
Features of the QCD Phase Diagram at Low Temperature and High Density
The 3-dimensional QCD phase diagram at high baryonic μ_B and moderate isospin μ_I densities has a rich and yet largely unexplored structure: a critical endpoint separates a smooth cross-over from a first order as well as a chiral phase transition at high baryon densities. New and exotic phases like quarkyonic matter or color superconducting phases might appear at baryonic high densities. At very high μ_B a superfluid color-flavor-locked phase is speculated on. Supernovae are formed at initial proton fractions ≈ 0.4 which reduce to ≈ 0.1 for cold neutron stars. Heavy-ion collisions at FAIR or NICA energies are expected to probe this region as well as the conjectured phase boundaries to quarkyonic or fully deconfined matter.

the $T - \mu_B$ plane by variation of the collision energy and the system size, looking for non-monotonicities or discontinuities in the excitation function of observables sensitive to the properties of the hot and dense matter. In the following, we discuss some of these observables.

The collective flow of hadrons is driven by the pressure gradient created in the early fireball, and thus provides information on the dense phase of the collision. In particular, the directed flow v_1 and the elliptic flow v_2 are expected to be sensitive to the details of the phase transition and the softening of the QCD matter EoS, and are important observables for clarifying the role of partonic degrees of freedom. Recently, the STAR collaboration has measured directed flow and elliptic flow in AuAu collisions at energies from $\sqrt{s_{NN}}$ = 62.4 GeV down to $\sqrt{s_{NN}}$ =7.7 GeV. A significant difference in the flow of particles and anti-particles is found at lower collision energies, i.e., with increasing μ_B. Moreover, both the sign and the magnitude of this difference are species-dependent. This points to the turn-off of the flow scaling with the number of constituent quarks, which is indicative for partonic degrees-of-freedom. However, at the lowest energy only pions, kaons, (anti-) protons and (anti-) Λ could be identified, and no firm conclusion on the origin of the species-dependent splitting could be reached. The data situation will drastically improve by measuring the flow of identified particles in the FAIR and NICA energy range, including multi-strange hyperons and di-leptons. Of particular interest is the flow of particles not suffering from rescattering like Ω hyperons or φ mesons, for which no experimental data exist. These measurements will significantly contribute to our understanding of the QCD matter EoS at neutron star core densities

Particles containing strange quarks are important probes of the excited medium created in heavy-ion collisions. At higher energies, strange particle yields are consistent with those expected from an equilibrated hadron gas. In particular, the equilibration of Ω baryons was taken as a strong argument for the system having undergone a transition to a deconfined state, since it cannot be understood in terms of hadronic two-body relaxation processes in the limited lifetime of the fireball. Following this argumentation, the yields of multi-strange hyperons are indicative for a deconfinement phase transition. This conjecture is supported by microscopic transport calculations modeling both a hadronic and a partonic phase, which find anti-hyperon yields strongly sensitive to a possible QGP phase.

According to hadronic transport models not featuring a partonic phase, multi-strange baryons are produced in sequential collisions involving kaons, Λ and, possibly, higher-mass resonances. Their yields are therefore strongly sensitive to the density of the fireball. This sensitivity is expected to increase towards lower beam energies close to or even below the production threshold in elementary collisions. Measuring the excitation function of multi-strange hyperons (Ξ^-, Ξ^+, Ω^-, Ω^+) in AA collisions with different A values is thus most promising to study the compressibility of nuclear matter at high densities and to determine the nuclear EoS.

The data situation for multi-strange hyperons in the SPS and AGS energy range is rather poor owing to the low production cross-sections. An intriguing result, however, has been reported at the lowest energies by the HADES collaboration: in Ar+KCl collisions at 1.76 AGeV, the measured yield of Ξ^- exceeds the Statistical Hadronization Model expectation by about a factor of 20, which indicates that the production of multi-strange particles is far off equilibrium at low energies. The measurement of these rare probes with high precision at future high rate experiments will decisively improve our knowledge on the nature and properties of the medium they are produced in.

Experimentally closely related to strangeness measurements is the study of *hyper-matter*, which has become a central topic for the attempts to model heavy neutron stars. Of particular importance for the understanding of the stability of such astrophysical objects is information on the hyperon-nucleon (*YN*) and hyperon-hyperon (*YY*) interaction. Experimentally, such information can be obtained by measuring *YN* and *YY* ($Y = \Lambda, \Xi, \Omega$) correlations, by measuring the production yields and lifetimes of hyper-nuclei such as ${}^{5}_{\Lambda\Lambda}H$ or ${}^{6}_{\Lambda\Lambda}He$, or by the search for exotica, like the hypothetical H-dibaryon $(\Lambda\Lambda)_b$ or other strange compound objects.

In heavy-ion collisions, hyper-nuclei may be produced by the coalescence of hyperons with nucleons or light nuclei in the final stage of the reaction. Thermal model calculations show that the most promising energy range is the FAIR/SIS-100 regime (Figure 6). Still, the expected yields for hyper-nuclei or strange dibaryons are very low and necessitate high-rate experiments. As an example, the CBM experiment promises to measure e.g., ${}^{5}_{\Lambda\Lambda}H$ and ${}^{6}_{\Lambda\Lambda}He$ in large quantities, which would represent a breakthrough in hyper-matter physics, as up to now only six candidates for double-Λ hyper-nuclei events have been found, and only one ${}^{6}_{\Lambda\Lambda}He$ event has been unambiguously identified.

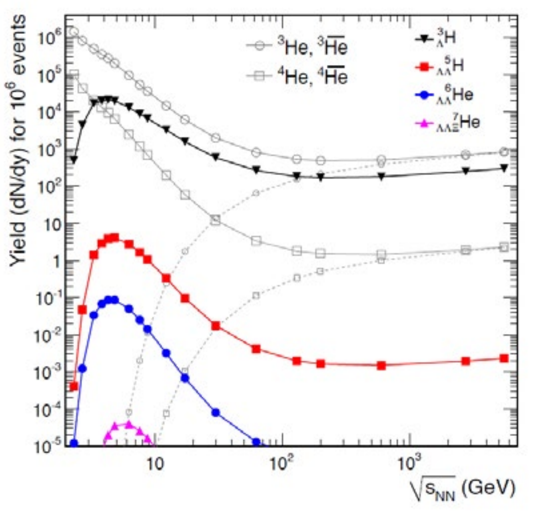


Figure 6: Energy dependence of hypernuclei yields at midrapidity for 10⁶ central AuAu collisions as calculated with the Statistical Hadronization Model. The predicted yields of ³He and ⁴He nuclei are included for comparison. From Phys. Lett. B 697 (2011) 203.

The *di-lepton radiation* carrying undistorted information from the fireball is an excellent tool to study properties of the strongly interacting matter in various aspects. Thermal radiation in the low-mass region (LMR) ($M < 1$ GeV/c^2) is saturated by spectral functions of the light vector mesons weighted by the temperature distribution and integrated over the collision time. It is a measure of the total lifetime of the fireball and hence can serve as a chronometer of the collision. Di-leptons in the LMR are also a sensitive observable to study chiral symmetry restoration as a function of T and μ_B. In the QCD vacuum, spectral functions of hadrons show splitting of parity doublets (i.e. the vector ρ and the axial-vector a_1) induced by the spontaneously broken chiral symmetry, which is predicted to vanish at high energy densities. A consistent explanation of the thermal di-lepton rates in the LMR, measured at SIS-18 (HADES), SPS (NA60/CERES) and RHIC energies, is given by the radiation from a strongly medium-modified ρ meson. As an example, Figure 7 shows the di-electron spectrum measured by HADES in AuAu collisions at 1.23 AGeV. The microscopic description is based on hadronic many-body theories with a dominant role played by the ρ-baryon interactions. The underlying connection to the chiral symmetry is provided by the QCD and Weinberg sum rules relating the spectral functions of the a_1 mesons with the quark and gluon condensates, which can be calculated by lattice QCD. Using such connections, it was shown for vanishing μ_B that the evolution of the a_1 spectral function with temperature is consistent with chiral symmetry restoration close to T_C.

The intermediate-mass region (IMR) from 1 to 3 GeV/c^2 provides an estimate of the temperature of the fireball at its early stage and hence can serve as a thermometer. Furthermore, the mass spectra are Lorentz-invariant and thus not affected by the collective expansion. On the other hand, transverse momenta and flow observables provide information on collective effects. At SPS and RHIC energies, the main contributions to IMR are given by QGP radiation, correlated heavy-flavour decays and charm annihilation. At lower energies, however, the charm contribution is decreased, and radiation from multi-pion annihilation, in particular a_1-π fusion and axial-vector mixing can be expected. It is therefore of utmost importance to provide high quality data at these energies in both the LMR, where the effects of baryons on the ρ meson are especially strong, and the IMR, where no data exist.

The interest in *charmed hadrons* is motivated by their unique role in the diagnostic of the highly excited medium created in high-energy nuclear collisions. As their mass is much larger than the temperature of the medium, charm quarks can only be produced in primordial hard processes in the first stage of the collisions. They thus probe the created medium during the entire evolution process. Suppression of charmonium states due to Debye screening by free colour charges was in fact the earliest proposed signature for deconfinement. The energy dissipation of the heavy quarks is considered the most promising probe for the characterization of the QGP formed in the early stages of the collision. After hadronisation, the then-formed charmed hadrons continue to interact through collisions with lighter hadrons. Understanding of this late-stage interactions is indispensable for a reliable characterisation of the QGP phase.

Studies investigating charm production were so far carried out at SPS, RHIC and LHC, where charm is produced with sizable cross-section. The results on charmonium indicate that at the later stages of the fireball evolution a significant degree of thermalization of the heavy quarks with the bulk medium consisting of light quarks and gluons is achieved. The large measured elliptic flow v_2 of *D* mesons underlines that heavy quarks take part in the collective motion of the bulk medium.

At lower collisions energies, where a medium with high net-baryon density is formed, the production mechanisms for charmed hadrons are likely to differ from those relevant at RHIC and LHC. Model predictions of the charm yield in this regime vary substantially, owing partly to the large uncertainty in the cc production cross-section, but also to the details of the formation of charmed hadrons. Because of the steep excitation function, the sensitivity to the details of the production mechanisms is largest near the kinematic threshold. Measurements of the yields of charmed hadrons at such energies can thus be expected to give decisive input to the theoretical understanding in this area, where no experimental data on charm production in heavy-ion collisions exist yet. Of particular interest is the question how far down in collisions energy the observations at RHIC and the LHC, attributed to the formation of a QGP, continue to hold. Heavy hadrons will thus be ideal probes to study the QCD phase transition in the high-μ_B domain.

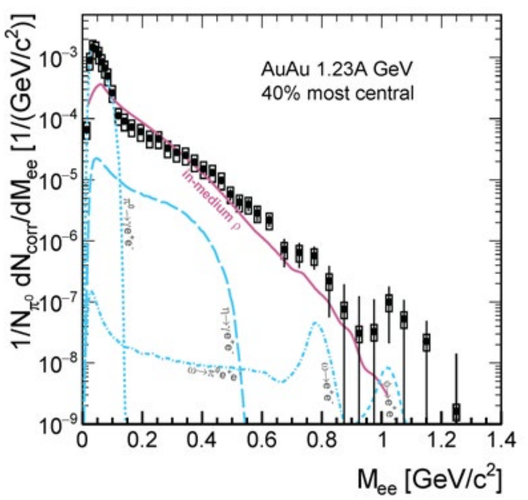


Figure 7: HADES results from AuAu at 1.23 AGeV: Invariant mass distribution of di-electrons (40% most central collisions). The data are compared to a cocktail of electron pairs from meson decays after freeze-out and contribution from in-medium ρ. From: HADES collaboration (priv. comm.), in preparation.

Event-by-event fluctuations of conserved quantities such as baryon number, strangeness and electrical charge can be related to the thermo-dynamical susceptibilities of the matter under investigation and thus are the prime tool to search for critical phenomena as expected in the vicinity of the QCD critical point, where the susceptibilities diverge in the limit of infinite matter. Hence, large non-statistical fluctuations are expected in heavy-ion reactions if matter is created at *T* and μ_B close to the critical point. It has to be noted, though, that the finite size of the system created in the collision limits the correlation length even near the critical point, such that quantitative predictions on the size of the fluctuations are not at hand. Simple arguments, however, show that the event-wise distributions become more and more non-Gaussian when approaching the critical point, such that higher moments grow faster with the correlation length than the quadratic ones. Higher moments (skewness, curtosis) are thus expected to be more sensitive to critical behaviour than just the width of the distributions.

Measurements have been performed by the STAR collaboration in order to search for the QCD critical point at beam energies down to $\sqrt{s_{NN}}$ = 7.7 GeV. Figure 8 depicts the product $\kappa\sigma^2$ of moments of the net-proton multiplicity distribution as a function of the collision energy, measured in central AuAu collisions. There are indications for a deviation from the Poisson expectation at the lowest measured energies. These data clearly call for a high-precision measurement of higher-order fluctuations at lower beam energies in order to search for the peak in $\kappa\sigma^2$ as expected in the presence of a critical point.

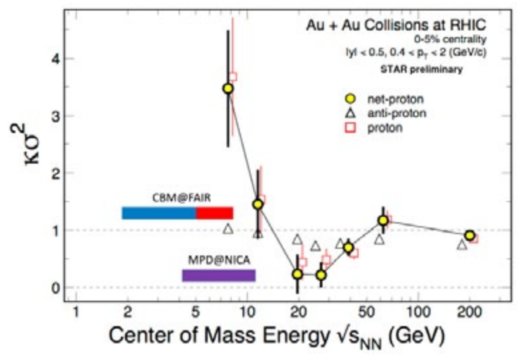


Figure 8: Energy dependence of the product of moments $\kappa\sigma^2$ of the net-proton multiplicity distribution (yellow circles) for top 0-5% central AuAu collisions. The Poisson expectation is denoted as dotted line at $\kappa\sigma^2 = 1$. From arXiv:1601.00951v2 [nucl-ex]. The solid bars indicate the energy ranges accessible by FAIR and NICA, respectively.

Current experimental activities

HADES at SIS-18 (GSI) is presently studying properties of strongly interacting matter with rare and penetrating probes at the low-energy frontier. The experiment has recently reached an important milestone by measuring AuAu collisions at 1.23A GeV. For the first time at such low energy, a complete measurement of strangeness production, i.e. *Λ, K, φ*, and low-mass di-leptons has been performed. The results indicate the formation of a long-lived system where sub-threshold particle production and di-lepton radiation is confined to the high-density phase of the collision. These results supplement those previously obtained by HADES with the medium-size collision system Ar+KCl and with p+Nb collisions where also the double-strange Ξ^- hyperon was measured. HADES also conducts a hadron physics programme with proton and pion beams focused on the role of baryon resonances in strangeness and di-electron production.

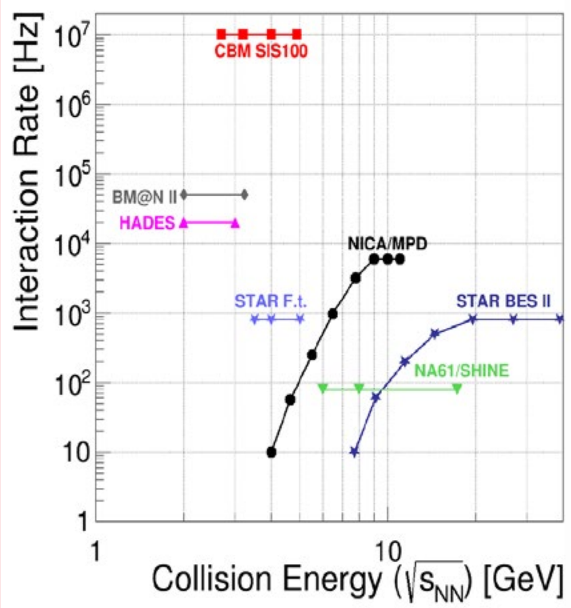
NA61/SHINE is a fixed-target experiment at the CERN SPS for the study of hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions. Its main physics goal is the study of the onset of deconfinement and the search for the critical point of strongly interacting matter. These goals are being pursued by investigating proton-proton, proton-nucleus and nucleus-nucleus collisions at different beam momentum from 13A to 158A GeV. Up to now, data from p+p, Be+Be and Ar+Sc collisions were taken at six different beam energies. The energy scan with medium-size (Xe+La) and heavy (Pb+Pb) systems are scheduled for the years 2017 and 2018. Beyond its approved programme, the collaboration plans for a detector upgrade including a silicon vertex detector for open charm measurements at the higher SPS energies and an extension of the programme by a few years.

NA61/SHINE has also a rich programme for a precise hadron production measurement. In this context, p+C and ρ, K, +C interactions were studied in the past years to provide improved calculations of the initial neutrino beam flux in the long-baseline neutrino oscillation experiments as well as more reliable simulations of cosmic-ray air shower.

Future plans

In the near future, two major accelerator facilities will come into operation, which will open up new possibilities for the exploration of high-density QCD matter with heavy-ion experiments. The Facility for Anti-Proton and Ion Research (FAIR), currently under construction in Darmstadt, will in its first stage provide nuclear beams up to 14 GeV per nucleon for symmetric nuclei and 11 GeV per nucleon for heavy ions with the SIS-100 synchrotron. In a later stage, a second accelerator (SIS-300) will extend the energy range to about 45 GeV per nucleon. At this facility, the Compressed Baryonic Matter Experiment (CBM) will measure both hadronic and leptonic probes with a large acceptance in fixed-target mode. For this next-generation experiment, the emphasis is put on very high rate capability, with the ambitious design goal of 10 MHz peak rate. Such interaction rates will overcome the limitations in statistics suffered by current experiments and permit the measurement of extremely rare probes like e.g., yields and flow of identified anti-baryons, in particular multi-strange hyperons, intermediate-mass lepton pairs, and particles containing charm quarks. The combination of high-intensity beams with a dedicated high-rate detector system provides worldwide unique conditions for a comprehensive study of QCD matter at the highest net-baryon densities achievable in the laboratory. Installation including commissioning of CBM is planned during 2021-2024. The nuclear collision programme at FAIR is complemented by the HADES spectrometer moved to the SIS-100 accelerator, which is well suited for reference measurements with proton beams and heavy-ion collision systems with moderate particle multiplicities, i.e. Ni+Ni or Ag+Ag collisions at the lower SIS-100 energies.

The new accelerator complex NICA at JINR Dubna will allow to study hot and dense strongly interacting matter at centre-of-mass energies up to 11 GeV per nucleon pair in collider mode. MPD is a collider experiment designed to perform a comprehensive scan of the QCD phase diagram with beam species from protons to gold by



Box 4
Overview on Experiments Exploring the High-density Region

Existing and future experiments will map out the phase diagram at different energies and interaction rates: the beam energy scan of STAR at RHIC connects the low and high μB regions. The future MPD experiment at NICA will measure excitation functions in the region of highest baryon densities. Both experiments, however, suffer from the typical decrease of luminosity at lower collider beam energies. The future experiment CBM at FAIR will run at substantially higher interaction rates. However, in order to fully map the region of high μB an upgrade of the SIS-100 to SiS-300 is mandatory. NA61 is a fixed target experiment at the SPS, which, however, is limited in rate by the TPC employed. HADES and BM@N cover a similar, -lower-, energy range. They have, however, a quite different focus with respect to observables.

varying the c.m.s. collision energy from 4 to 11 GeV per nucleon which complements the RHIC beam energy scan towards lower energies. The MPD acceptance ($|\eta| < 3$, $0 < p_T < 3$ GeV/c, and full azimuthal coverage) and relatively high event rates (up to 10 kHz, see Box 4) make it an ideal detector to study event-by-event fluctuations and azimuthally sensitive observables. The unique feature of MPD as a collider experiment is the invariant acceptance at different beam energies as compared to fixed-target experiments. This, however, is counter-balanced, as for all collider experiments, by a sizeable decrease in interaction rate at lower energies (see Box 4). Thus, the study of rare probes such as di-leptons, φ, Ξ, and Ω, is restricted to the higher beam energies. MPD will start operation in a staged approach, with first beams in the NICA collider expected in 2019 and reaching its full capabilities by 2023.

Extracted beams from the NICA facility will also allow a fixed-target programme in a limited energy range but with higher interaction rates. The BM@N experiment, currently being constructed, plans for data taking at the NICA nuclotron with heavy beams up to 4.5 GeV per nucleon from 2019 on. It will measure yields and flow of identified hadrons at interaction rates of up to 50 kHz.

Outside Europe, the STAR collaboration plans a second phase of the RHIC beam energy scan programme (BES-II) in the years 2019-2020, with increased statistics owing to an upgrade of the RHIC accelerator with electron cooling, and with improved detector performance resulting from an upgrade of the existing time-projection chamber. The programme focuses on fluctuation and flow measurements in search for the QCD critical point. While being less sensitive at low energies because of limited statistics, BES-II will extend the energy range accessible by FAIR and NICA to higher energies and is thus complementary to the FAIR and NICA plans. In addition, STAR also plans to take data in fixed-target mode by inserting a target in the beam halo. This would give access to bulk probes in the low-energy range.

Together with the programmes at SPS and RHIC, the new experiments at FAIR and NICA will provide a complete coverage of the energy range relevant for the investigation of QCD matter at large net-baryon densities, albeit with varying sensitivity depending on the accessible interaction rates. The running and planned experiments show a large degree of complementarity, e.g., in terms of acceptance or run mode (fixed target / collider). The experimental landscape is summarised in Box 4, showing the coverage in energy range and interaction rates of the various experiments.

Beyond the future experiments already under construction as outlined above, there are plans for further experimental projects, which are yet in a conceptual stage. The project NA60+ aims at a high-precision study of thermal radiation and charmonia by the measurement of muon pairs in fixed-target nuclear collisions at the SPS, with an experimental concept similar to that of the NA60 detector. Such measurements would be complementary in energy range to the muon programme of CBM, and complement the programmes of RHIC-BES, NA61 and MPD in the same energy domain, which do not have access to muon measurements. Furthermore, plans for a heavy-ion physics programme at J-PARC, Tokai, are currently under consideration. These would add an additional heavy-ion accelerating scheme to the current facilities, providing extracted heavy-ion beams up to 19 GeV per nucleon for fixed-target experiments. The aim is also to arrive at very high beam intensities, comparable to those at FAIR.

PERSPECTIVES ON FACILITIES, COMPUTING AND INSTRUMENTATION

Facilities and Experiments Several facilities in Europe are currently in operation, in construction or in discussion, to provide heavy-ion collisions at various energies, to explore different regions of the phase diagram. We give a brief overview of the facilities and the relative experimental programmes for the next decade. We start from facilities which are existing and operating (the LHC), continue with those whose realization is already approved and on-going (FAIR and NICA), and then discuss further plans which are under exploration for the future (NA60+ at the SPS, AFTER at the LHC, the Future Circular Collider).

LHC Run-3 and Run-4 and relative upgrades LHC experiments made terrific steps forward in the comprehension of the QGP using Run-1 (2009-2013) data. The higher statistics which is being recorded during the on-going Run-2 (2015-2018) will further solidify the physics programme which was planned for the first inverse nanobarn of integrated luminosity. Nevertheless, the precise determination of several observables in PbPb interactions and the study of the rarest probes require a higher integrated luminosity. With a ten time larger data sample and upgrades of the detectors, the experiments will address the following topics (among others): the study of charm and beauty quark production down to very low transverse momenta and their possible thermalization in the medium; the elliptic flow of prompt *J/ψ*, the measurement of the *J/ψ* polarization and the study of the *ψ(2S)* with uncertainties as low as 10% down to zero p_T ; a precise investigation of the jet structure as well as jet-photon and jet-Z^0 correlations; the study of the production of light nuclei, hyper-nuclei, and the search for exotic compound hadrons; the measurement of low-mass di-leptons to give a determination of the temperature of the source emitting the thermal di-leptons: an integrated luminosity of 10 nb^{-1} would allow a statistical precision of about 10% and a systematic uncertainty of about 20%.

The main strategy to increase the luminosity in the PbPb Run-3 and Run-4 at the LHC is to increase the total number of lead nuclei stored in the machine. This goal can be achieved by reducing the bunch spacing within the PS batches and/or decreasing the SPS kicker rise time to reduce the bunch spacing in the SPS. A peak luminosity exceeding $6 \cdot 10^{27} cm^{-2}s^{-1}$ can be achieved. The actual schedule foresees 2.85 nb^{-1}/year integrated luminosity, starting from 2021. The LHC schedule for the present Run-2 and the future runs is shown in Figure 9, which emphasizes the heavy-ion periods and reports the integrated luminosity requested by the ALICE experiment.

From 2021 on, the LHC will operate at the nominal center-of-mass energy of 14 TeV for proton-proton and of 5.5 TeV per nucleon pair in PbPb collisions, and will make a significant step forward in the luminosity. The long shutdown LS3 will prepare the machine and the experiments to a further jump of a factor 10 in proton-proton luminosity, with the High-Luminosity LHC entering operation in 2026 with two runs presently foreseen (Run-4 and Run-5). Concerning PbPb collisions, for Run-3 and Run-4 the experiments have requested a total integrated luminosity of more than 10 nb^{-1} (e.g., 13 nb^{-1} requested by ALICE) compared to

Figure 9: The LHC schedule for the next runs.

the ~ 0.1 nb^{-1} recorded in Run-1 and the expected ~ 1 nb^{-1} of Run-2. During Run-3 and Run-4, reference samples with pp collisions at 5.5 TeV will also be collected, as well as a sample with pPb collisions at 8.8 TeV. The possibility of extending the programme to collisions of nuclei lighter than Pb (e.g. Ar-Ar or O-O) is under discussion.

The ALICE Collaboration is preparing a major upgrade of the experimental apparatus that will operate during Run-3 and Run-4. The upgrade strategy was driven by the following requirements:

- Improvement of the track reconstruction performance in terms of spatial precision and efficiency, in particular for low-momentum particles to select more effectively the decay vertices of heavy-flavour mesons and baryons, and study better the production of low-mass di-electron pairs;
- Increase of the event readout rate up to 50 kHz for PbPb collisions with a minimum-bias selection, providing the highest efficiency for low-momentum processes. This luminosity enables recording during Run-3 and Run-4 of a sample of minimum-bias collisions two orders of magnitude larger compared to Run-2;
- Consolidation of the particle identification capabilities of the apparatus, which are crucial for the selection of heavy flavour, quarkonium, di-lepton, and nuclei decay products at low momentum.

The ALICE upgrade programme entails the following changes to the apparatus: a new Inner Tracking System (ITS) with seven layers equipped with Monolithic Active Pixel Sensors (MAPS), a Muon Forward Tracker (MFT) made of five planes of the same MAPS used in the ITS, new readout chambers for the TPC based on the Gas Electron Multiplier (GEM) technology and a new Fast Interaction Trigger detector (FIT) based on Cherenkov radiators and scintillator tiles at forward rapidity around the beam pipe. The upgrade includes the readout electronics of most of the detectors to record PbPb interactions at a rate of up to 50 kHz, and a new integrated Online/Offline system for data readout, compression and processing to reduce the volume of data by more than one order of magnitude before shipping them to permanent storage.

The other major LHC experiments have planned rich heavy-ion programmes, also taking profit of the major upgrades of the detectors scheduled up to LS3. For instance CMS will upgrade the pixel system, the inner tracker, the trigger and the data acquisition systems, among other upgrade projects. These improvements will allow the full exploitation of the high luminosity heavy-ion running for jet quenching analyses and will improve the heavy-ion reconstruction performance to about the level of the current pp reconstruction algorithms. Moreover, very precise measurements of the production of quarkonium states and electroweak bosons will be achieved, as well as new measurements never attempted before, as the production of top quark in heavy-ion collisions. The LHCb experiment has joined the LHC heavy-ion programme at the end of the Run-1, and has performed key measurements of charm and quarkonia in p-Pb collisions. LHCb has excellent capabilities complementary to those of the ALICE experiment in the measurement of pA collisions. In 2015, LHCb has started to explore their capabilities in PbPb collisions at 5 TeV and to test the possibility of performing fixed-target measurements at the LHC with the SMOG system. A gas is injected in the beam pipe, to collide with the LHC beams: various nuclei were tested so far (He, Ne, Ar), demonstrating the feasibility of such a programme. SMOG results are extremely promising and show the absence of impact of the gas injection on the LHC. LHCb has planned a large upgrade of its detector during LS2, namely its tracking system. LHCb will certainly make important contributions to the heavy-ion programme at the LHC during Run-3 and Run-4. Proton-lead collisions at the highest LHC energies are also of interest, since they allow the exploration of the formation of a semi-classical state of gluon fields, the Color Glass Condensate.

Currently, the heavy-ion programme at the LHC is effectively restricted to the use of one ion type per year: the setup time of the current ion source at CERN is of a couple of weeks. Therefore different ions can be used, but both a switch between different types and having collisions between different ions is practically not possible within the normally foreseen four weeks of heavy-ion programme per year. Recently the possibility to study collisions between lead ions and deuteron or ^{3}He, in addition to pPb, was considered with great interest. Also the possibility to having asymmetric collision systems (as Cu+Au was done at RHIC) could be studied. A second ion source is in discussion at CERN, in connection to medical applications too. That might provide light ions like deuteron and ^{3}He, although that might take until 2030.

Very large new facilities are currently under construction: FAIR and NICA.

Using the current GSI facilities as injector chain, the FAIR centre (in Darmstadt, Germany) will comprise two synchrotrons and a complex system of storage rings that will provide both internal and external beams for a variety of physics programmes, ranging from QCD matter physics over hadron physics with anti-proton beams and nuclear structure physics with rare-isotope beams to applied and plasma physics with ultra-high intensity, bunched beams. Among these programmes, heavy-ion collision physics is one of the major scientific pillars of the FAIR project. For this research field, the accelerator complex will deliver a large variety of extracted, fully stripped ion beams (e.g., p, C, Ca, Ni, Ag, Au) with unprecedented intensities of above 10^9/s, thus enabling fixed-target experiments with extreme reaction rates. In the first stage of FAIR, planned to start operation in 2024, the SIS-100 synchrotron with a bending power of 100 Tm will accelerate heavy ions to 11A GeV, symmetric nuclei up to 15A GeV and protons up to 29 GeV. At a later stage, a booster ring (SIS-300) with 300 Tm bending power or more can be installed in the same tunnel. Beams injected from the SIS-100 will be accelerated to 35A GeV (heavy ions), 45A GeV (medium-size ions) and 90 GeV (protons). Apart from the extension of the energy range, the SIS-300 will enable a highly parallel operation of the various physics programmes of FAIR, thus substantially increasing the available experiment time for each of those.

The nuclear collision programme at FAIR will be conducted by the CBM experiment, currently being designed to operate at SIS-100, with well defined upgrade options for a possible later use at SIS-300, and the HADES detector, which is currently in operation at the SIS-18 accelerator at GSI and which will be moved to the SIS-100 beam line. CBM will be a next-generation experiment being able to cope with the complex event topologies typical for heavy-ion reactions at very high interaction rates of up to 10^7 collisions per second, more than two orders higher than that of other existing or planned detectors in the field. To achieve this ambitious goal, rigorous R&D on innovative technologies for detectors, electronics and data processing was performed over the last decade, with the emphasis on fast and radiation-hard detectors and electronics.

The backbone of CBM is a low-mass Silicon Tracking System (STS) based on double-sided silicon strip sensors, which is hosted in the aperture of a dipole magnet of about 1 Tm bending power. In order to achieve the design goal of a momentum resolution of 1.5%, the readout electronics will be placed outside of the acceptance and will be connected to the sensors with low-capacity, ultra-thin cables. The tracking capabilities of CBM will be enhanced by a Micro-Vertex Detector (MVD), using the Monolithic Active Pixel Sensor (MAPS) technology to determine secondary vertices of open charm decays and to enhance the background rejection capabilities for di-electron studies. The envisaged interaction rates require a time resolution of 10 μs or below and sufficient radiation hardness to stand more than 10^{13} neq/cm^2, figures which after several years of R&D are now within reach.

The major technological challenges for the Time-of-Flight Detector (TOF), using multi-gap Resistive Plate Chambers, and the Transition Radiation Detector (TRD) based on MWPC readout is the development of highly granular and fast gaseous detectors which can stand the CBM environment in particular for the inner part covering forward emission angles. Several advances in detector technology allow now to operate these detectors at very high rates and with good resolution.

The flexible and modular design of the CBM detector system allows for both hadronic and leptonic observables. The latter, i.e., di-electrons and di-muons are addressed with a Ring Imaging Cherenkov (RICH) detector, comprising a radiator and a UV photon detector realized with multi-anode photomultipliers for electron identification, and a Muon Chamber System (MuCh) for muon identification, consisting of a GEM-instrumented hadron-absorber made of graphite and iron plates. Furthermore, an Electromagnetic Calorimeter (ECAL) based on lead-scintillator layers will be used to measure photons and neutral mesons (π^0, η) decaying into photons. The detector setup is completed by a forward calorimeter, the Projectile Spectator Detector (PSD), providing measurements of centrality and reaction plane.

A particular challenging feature of CBM is the processing of the large amount of raw data delivered by the detector systems, which requires an online reduction of the data rate by more than two orders of magnitude when running at the highest interaction rates. As most of the rare key observables of CBM have rather complex signatures not allowing for a conventional hardware trigger, CBM employs a novel data acquisition system with trigger-less electronics, shipping time-stamped raw data to an online computing farm. There, event reconstruction and data selection will be performed in real-time by dedicated software. This necessitates very fast and highly parallel algorithms, which reconstruct 4D event topologies (i.e., in space and time), coping with the temporal event overlap at high rates. Prototypes of such algorithms have been developed in the past years, providing a step towards the required performance.

In parallel to the construction of FAIR, the accelerator facilities at JINR Dubna are being substantially enlarged by the NICA project, which will support world-leading programmes in relativistic nuclear physics and particle spin physics, radiobiology, applied research and education. The main goal of the project is the study of hot and dense strongly interacting matter in heavy-ion collisions (up to Au) at centre-of-mass energies up to 11A GeV. Both colliding and extracted beams will be delivered to the experiments MPD and BM@N, respectively (see below). The study of spin physics with beams of polarized protons and deuterons is foreseen as well.

The NICA accelerator facility is being developed in three stages. The first stage comprises the construction of the new injector, the booster-synchrotron and commissioning of the BM@N detector with planned start of operation for fixed-target experiments in 2017, based on the Nuclotron providing $^{197}Au^{79+}$ ions with a kinetic energy in the range of 1-4.5 GeV/u and protons up to 12.6 GeV. In the second stage, the collider, the beam transfer line from the Nuclotron to the collider, and the multi-purpose detector (MPD) will be constructed. The two SC collider rings have a circumference of 503 m each. In order to reach the design luminosity of 10^{27} cm^{-2} s^{-1} for Au ions, both electron and stochastic cooling systems will be provided. The mass production of the magnets (prototypes were tested in 2013) is scheduled for 2016-2018. The construction of the collider buildings and the transfer channels was started in November 2015. The mounting of the collider elements, the transfer channel and parts of MPD is planned to be started beginning 2019. The start-up version of the project is planned for the end of 2019, the completion of commissioning for 2023. In the final stage of NICA, polarized ion beams (starting with deuterons, based on experience with the Nuclotron since the beginning 1990s) and the construction of the spin-physics detector (SPD) at the second interaction point, opposite to the MPD, are planned.

QCD matter physics at the new collider will be studied by the MPD detector, being designed to record heavy-ion induced reactions at intermediate reaction rates (see Box 4). The detector system, housed in a 0.66 T superconducting solenoid, will measure charged hadrons, electrons and photons. In its first stage the MPD will comprise a Time Projection Chamber (TPC) with a design similar to the existing ALICE TPC covering a pseudorapidity range $|\eta| < 1.2$. The chamber is designed for a momentum resolution below 3% in the range $0.1 < p_T < 1$ GeV and a dE/dx resolution below 8%. A multi-gap resistive plate Time-of-Flight Barrel (TOF) supplements the particle identification of the TPC with a design time resolution of below 100 ps. The start time for the time-of-flight system is provided by a Fast Forward Detector (FFD), which also provides a L0 collision trigger. The FFD converts forward photons in a lead converter. The ensuing Cherenkov light is detected in MCP photomultipliers providing a high-resolution timing signal. An Electro-Magnetic Calorimeter Barrel (ECAL) will provide electron and photon identification with an energy and time resolution of ≈ 2.5%/√E and 80 ps, respectively. The current design of the ECAL is of the so-called "shashlyk" type (lead-scintillator sandwich). Finally, a lead-scintillator Forward Hadron Calorimeter (FHCAL) will serve for centrality and event plane determination. In a second, later stage the MPD detector will be supplemented by a silicon-based Inner Tracker and end-cap detectors (tracker, time-of-flight and EM-calorimeters) which will make it a versatile 4π heavy-ion detector.

The BM@N fixed-target experiment will make use of extracted beams from the upgraded Nuclotron. The experiment combines high precision track measurements with time-of-flight information for particle identification and uses total energy measurements for the analysis of the collision centrality. The charged track momentum and multiplicity will be measured with a set of two coordinate planes of GEM Detectors (Gaseous Electron Multipliers) located downstream of the target in the analyzing magnet and the Drift/Straw Chambers (DCH, Straw) situated outside the magnetic field. The GEM detectors sustain high particle rates of particles and can be operated in the strong magnetic field. The design parameters of the Time-of-Flight detectors based on Multi-Gap Resistive Plate Chambers (mRPC) with a strip read-out allow to discriminate between hadrons (π, K, p) as well as light nuclei with momenta up to few GeV produced in multi-particle events. A Zero Degree Calorimeter (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward going particles.. Processes with electro-magnetic probes (γ, $e^{\pm}$) in the final state will be measured by an Electro-Magnetic Calorimeter installed behind the outer drift/straw chambers and the mRPC wall.

In addition to the existing facilities and those under construction, other proposals and major projects are being worked on and discussed in the scientific community.

AFTER@LHC is the project of a fixed-target experiment at the LHC for hadronic, spin and heavy-ion physics based on four crucial advantages of the fixed-target mode with TeV beams: high luminosities, an access to target rapidities (y), target versatility and polarisation. This allows for extremely precise studies of most hard probes in many colliding systems over the whole y<0 region thanks to the boost. These, along with an ambitious spin programme, complement the scope of RHIC and the Electron Ion Collider project. To name a few, AFTER@LHC gives access to measurements, at an energy between RHIC and SPS, of the entire bottomonium family, of a complete set of charm observables down to low p_T (e.g. ψ, χ_c, D,D+D, ψ+D and the corresponding ratios), of the Drell-Yan process in pA, Pbp and PbA collisions to check, for the first time, the nuclear PDF factorisation. In addition it will allow the study of azimuthal asymmetries over the entire negative y to understand their origin and the measurement of the temperature dependence of the shear viscosity. AFTER@LHC also offers a unique range of opportunities for pA studies at large x where many nuclear effects remain poorly understood.

The project NA60+ aims at high-precision measurements of thermal radiation, light vector mesons and charmonia via the detection of muon pairs to explore the phase diagram at moderate-to-high baryonic density and to look for chiral symmetry restoration, the on-set of deconfinement and the critical endpoint. It consists in a beam energy scan at the CERN SPS from 20 to 160 GeV per nucleon with a fixed target detector, complementary to SIS-100, SIS-300 and NICA. It complements NA61 focused on hadronic observables. The NA60+ experimental concept is similar to that of the previous NA60 experiment at the SPS with a vertex spectrometer, a hadron absorber and a muon spectrometer with a readout system of several tens of kHz. NA60+ will have unique capabilities to perform the above mentioned studies, in the energy range of the RHIC energy scan and NICA.

In February 2014, CERN launched an international design study for a Future Circular Collider (FCC) to assess the feasibility and physics potential of a new hadron collider providing proton-proton collisions at a center-of-mass energy of 100 TeV, in a 80-100 km tunnel near Geneva. The study aims at a possible starting time in 2035-2040. The operation with heavy ions is part of the accelerator design studies. The center-of-mass energy per nucleon pair would be 39 TeV and 63 TeV for PbPb and proton-Pb collisions, respectively. Even in a conservative injection scenario, the new accelerator could provide an integrated luminosity as high as 33 nb^{-1} per month of running. The higher collision energy and the increased integrated luminosity open tremendous opportunities in the investigation of the QGP at vanishing baryon chemical potential. A medium which is initially denser and hotter will be created, which will also have a longer expansion time, over a larger volume: stronger collective effects and novel qualitative phenomena may become accessible. Hard processes will become available in much larger abundance, thanks to both the higher center-of-mass energy and the larger statistics: this not only holds for heavy quarks and high-momentum jets, but will also allow to study the interaction of the top quark with the QGP, to probe the time evolution of the QGP density and the role of colour coherence. Collisions at the FCC will also allow to probe saturated parton densities in a totally new ultra-dense kinematic region. The possibility of a heavy-ion physics programme at the FCC is currently being discussed.

Computing Resources

All present and future research projects dedicated to study the properties of strongly interacting matter require large computational resources. Adequate computing power and infrastructures are needed both by theory and experiments.

Computing infrastructure for theory will require large-scale resources to cope with the demanding requests driven by high-precision calculations. Numerical simulations by lattice-regularized QCD (lattice QCD in the following) have developed rapidly and very successfully in the last years. By implementing non-perturbative techniques, lattice QCD calculations provide estimates of the QCD EoS and the critical behavior at vanishing chemical potential, and important developments to extend to the non-zero potential regime and the determination of transport coefficients are taking place.

These computations employ high performance computers with the power of the Pflop/s order and involve the use of accelerators like GPUs. The resource needs grow with a doubling time of approximately 1.5 years, consistently with Moore's law, and will continue growing rapidly in the coming years. The planned future developments require more numerous or larger computational resources: multi-GPU architectures and resources with many thousands of GPUs or new many core CPU architectures are needed to carry out computations approaching the chiral limit, calculations of higher-order cumulants, thermal masses and transport properties. At the same time, appropriate support for software developments must be secured: new software will be needed to exploit fully the new hardware architectures especially as most of them will have more complex memory hierarchies. Moreover important progress can be achieved with the development of new and optimized algorithms.

As far as the computing for experiments is concerned, in the coming years the existing infrastructures for physics analysis and simulation, like the WLCG used for the ALICE experiment at the LHC, have to be maintained and scaled up to meet the demands in the next decade.

High-luminosity accelerators and advanced detector technologies result in a dramatic increase of data sizes (several orders of magnitude) and bandwidth into the computing systems. Both the upgraded detectors of the ALICE experiment at the LHC for Run-3 and Run-4, and the two big data producers at FAIR, CBM and PANDA, will provide data outputs in the order of Terabytes/s. New and by now matured technologies like distributed cloud systems and the availability of high-bandwidth wide area networks offer new opportunities for international collaborations, however, require further development of the computing models. In addition the rapid technology development in terms of the density of compute power and the bandwidth available for data storage, led to a shift of paradigm for the design of the experiments. High-rate data taking will be not enabled by hardware triggers, but by reconstructing and selecting physically interesting data in real-time. This requires a significant investment in the online computing systems: large on-site computer facilities and storage capacities will be decisive for the physics reach in terms of collected event statistics.

The strong development of online computing has also consequences for the offline computing models and needs. The online clusters will be composed of commercial off-the-shelf hardware, which can also be used for offline computing in the experiment downtimes. In general, offline computing will shift away from the GRID approach, towards a small number of big data centres connected by high-speed networking, which offer computing access to a regionally defined group of users.

To make efficient use of modern computing hardware, both for online and offline purposes, parallel programming is indispensable. The needed software skills exceed those that nowadays can be assumed for the average physicist. This situation calls for an increased effort in training on modern programming technologies, but also for the development of adequate data processing frameworks by experts. In the recent years, we have seen a significant common development effort between the major experiments and nuclear physics laboratories. The FAIR experiments and the ALICE experiment at the LHC have embarked to develop a common software framework (ALFA), based on the successful experience with the FairROOT framework developed at GSI. This new open-source framework will be the basis of the experiment-specific software developments for the next decade. The new framework enables the experiments to fully exploit the capabilities offered by modern computing systems and reduces the development and maintenance costs.

New computing solutions are continuously emerging: in the last decade, the architecture of computing systems has rapidly changed, mainly driven by the demands of the digital economy. The transition from single-core to multi-core architectures with wide vector processing units, accelerator cards like GPUs, the availability of commercial high-speed networks as well as tiered memory and storage solutions changed the way in which algorithms need to be implemented. On the infrastructure side, modern data center facilities characterized by a high performance coupled with a low power usage are required. As an example, the "Green Cube", at GSI, is an energy and cost saving, high performance data center: it will accommodate powerful energy-efficient super-computers, taking advantage of a new water cooling concept, whose capacity will exceed 10 MW.

Meeting the future computing demands of the nuclear physics community in a cost-effective way, needs fully exploiting the capabilities of the rapidly evolving computing landscape.

Forthcoming Detector Challenges and New Instrumentation

High intensity facilities proposed for the next years require outstanding detectors to cope with the high interaction rate, measurement precision and particle identification capability. Detector R&D is a key tool for a successful planning of the next generation of nuclear physics experiments exploring the QCD phase space.

GEM-based high resolution TPC

The operation of a traditional TPC, e.g., with Multi-Wire Proportional Chamber (MWPC) based read-out plane and gating grid, has a principal limit of the triggered rate of few kHz. The expected increase of the LHC luminosity after the LHC long shutdown 2 in 2019/20 (LS2) to 50 kHz in PbPb collisions, implies that a gated TPC is no longer a sensible mode of operation.

An alternative readout scheme based on GEM foils, which will allow for non-triggered, high rate operation, has been chosen by ALICE. Readout chambers with GEM stacks feature inherent suppression of the ion back flow (IBF) into the drift region. IBF is responsible for track distortions, whose magnitude depends on the quasi-static charge density created by the ions drift region. The ALICE collaboration showed that the IBF can be limited to 1%, achieving a dE/dx resolution of about 5-6%, as in conventional MWPC-based TPCs.

Precise vertexing and tracking accuracy in high particle density

Tracking with high space accuracy and precise vertexing capabilities in relativistic heavy-ion collision experiments represent a challenge due to the very high particle density. In the next years, the two larger high energy nuclear physics experiments at European facilities, ALICE at CERN and CBM at FAIR, will adopt CMOS Monolithic Active Pixel Sensors (MAPS) for vertexing and tracking in the proximity of the interaction point. After an intense R&D effort, this technique showed a space resolution better than 10 μm, a power consumption <100 mW/cm^2, and radiation hardness at a total integrated dose up to few Mrad. The ALICE time schedule foresees the installation of these new detectors during the LHC LS2 (2019-2020).

Ultra fast silicon detectors for 4D tracking

Ultra fast silicon detectors (UFSD) are a promising device, taking advantage of the intense R&D performed in the CERN RD50 collaboration and INFN Gruppo V. UFSD aim at providing a 4D event reconstruction with a space resolution ranging between 20 and 50 μm and a time resolution of 10-20 ps. Such an excellent time resolution requires large and fast signals. The basic idea is to use n-on-p low-gain avalanche detectors (LGAD) with a high ohmic p bulk with a p+ implant extending several microns underneath the n-implant. The p+ plant provides a large electric field, 300 kV/cm, allowing avalanche multiplication and high drift velocity, while thin devices ensure large signal slope dV/dt (slew rate) and are less sensitive to total dose radiation effects. Test beam results based on 300 μm thick device showed a time resolution of 120 ps; according to detailed simulations this time resolution corresponds to about 30 ps for a 50 μm thick device presently in construction. This device can be used for particle identification in TOF detectors, fast triggering and forward physics.

Compact RICH detectors

Future heavy-ion experiments have to foresee detectors with PID capability, too. Cherenkov detectors are successfully used in several experiments and various typologies of Ring Imaging Cherenkov detectors (RICH) are planned in the next years. Important progress has been reached by CBM at FAIR, that includes a gas RICH to identify electrons up to 8 GeV/c. Photons generated in the CO_2 radiator (typically 20 hits/ring) will be detected by 1,100 multi-anode photomultipliers. At high momentum, radiators with a low refractive index are required, resulting in a small number of photoelectrons. This could drive up the detector length and cost. At momenta of few GeV/c, silica aerogel offers an affordable solution while beyond 10-15 GeV/c other solutions should be considered. Compact RICH can be built using gas under pressure, as pressurized octafluorotetrahydrofuran (C_4F_8O), and an appropriate focusing geometry. Recently more than 10 photoelectrons have been obtained with a 1 m long prototype RICH using C_4F_8 as radiator and a GEM stack structure to detect photons. A clear *π, K, p* separation up to 32 GeV/c has been obtained by a prototype exposed to the Fermilab beam test facility.

Silicon Calorimeters

The study of electrons and photons at high rapidities in collider experiments requires compact, highly segmented and fast calorimeters with imaging capability, to associate the energy depositions with the showers originating from individual particles. Electromagnetic showers have to be confined in small volumes to avoid overlaps and therefore a proper segmentation is required. Silicon detectors coupled with a tungsten absorber are a good candidate, coping with all the above requirements. In addition silicon calorimeters show a very good radiation hardness. Several calorimeters relying on few tens of layers and segmentations of few squared millimeters have been developed in several R&D projects: a good linearity coupled with a satisfactory energy resolution (σ/E) ranging between 15%/√E to 30%/√E, depending on the sampling fraction, has been achieved. Silicon calorimeters have been proposed by the experiments ALICE at the LHC (FOCAL) and PHENIX at RHIC (MPC-EX).

RECOMMENDATIONS

Experimental programme

- Vigorous efforts should be devoted to the continuation of the heavy-ion programme at the LHC with Runs 3 and 4, including man-power support and completing the planned detector upgrades.
- At intermediate energies, we recommend the continuation of the on-going programmes: HADES at SIS-18, NA61 at the SPS.
- In order to investigate nuclear matter at high

baryonic density, the timely construction of SIS-100 at FAIR and the realization of the CBM experiment are of utmost importance.

- In parallel, efforts should continue in order to support developments for a future SIS-300 upgrade.
- We recommend the completion of the BM@N experiment at JINR, and the construction of the NICA facility and the realization of the associated MPD experiment.
- Exploratory studies on prospective future heavy ion projects, namely AFTER@LHC, NA60+ at the SPS, and a heavy-ion programme at the Future Circular Collider, should be continued.

Theory developments

- Theoretical work in the field of heavy-ion collisions should be guaranteed continuous support, both in its phenomenological aspects (theoretical support needed to interpret the results and to provide feedback to the experimental programme) and in its more ab initio works (quantum chromodynamics).
- A close collaboration between theorists and experimentalists should be encouraged and nurtured, since most progress in heavy-ion physics stems from a continuous exchange between them.

3

NUCLEAR STRUCTURE AND REACTION DYNAMICS

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3. NUCLEAR STRUCTURE AND REACTION DYNAMICS

INTRODUCTION

The strong interaction described by quantum chromodynamics (QCD) is responsible for binding neutrons and protons into nuclei and for the many facets of nuclear structure and reaction physics. Combined with the electroweak interaction, it determines the properties of all nuclei in a similar way as quantum electrodynamics shapes the periodic table of elements. While the latter is well understood, it is still unclear how the nuclear chart emerges from the underlying strong interactions. This requires the development of a unified description of all nuclei based on systematic theories of strong interactions at low energies, advanced few- and many-body methods, as well as a consistent description of nuclear reactions.

Nuclear structure and dynamics have not only reached the discovery frontier (e.g. focused on new isotopes, new elements, ...), but are also entering into a high precision frontier with higher beam intensities and purity, along with better efficiency and sensitivity of instruments, in order to focus on essential observables to validate and guide our theoretical developments.

These developments are closely connected to the existing and new high-intensity stable and radioactive ion beam facilities in Europe, especially conceived to study the structure of exotic nuclei. For instance, the study of nuclear ground- and excited-state properties is vital in revealing the role played by the strong interaction in atomic nuclei and in understanding nuclear structure phenomena and their emergence from fundamental interactions. The fragmentation facility FAIR, the in-flight separator ACCULINA-2 and the low-energy ISOL facilities HIE-ISOLDE, SPES and SPIRAL2, which will provide re-accelerated radioactive ion beams, are being developed and their construction should be vigorously pursued to start the exciting physics programmes in the coming decades. Stable beam facilities will continue to perform vital science programmes in the study of exotic nuclei at the extremes of isospin, angular momentum and temperature. In addition, the structure of the heaviest elements will be further explored with high-intensity stable beams at JYFL, GSI, GANIL-SPIRAL2 and at the JINR-SuperHeavy Elements Factory. The brilliant gamma-ray beams from ELI-NP will open up new perspectives using electromagnetic probes, complementary to the other nuclear physics research facilities. Finally, breakthrough research in theoretical nuclear physics relies on continued access to national and European high-performance computing facilities with leading edge capabilities.

With the development of these new and upgraded facilities, new instrumentation and advanced techniques, Europe will continue to play a leading role in nuclear structure research in the coming decades. These activities will be complemented by experimental programmes headed by European teams at leading international facilities outside Europe. The access to new and complementary experiments combined with theoretical advances allows key questions to be addressed such as:

How does the nuclear chart emerge from the underlying fundamental interactions?

Where are the limits of stability and what is the heaviest element that can be created?

How does nuclear structure evolve across the nuclear landscape and what shapes can nuclei adopt?

How does nuclear structure change with temperature and angular momentum?

How can nuclear structure and reaction approaches be unified?

How complex are nuclear excitations?

How do correlations appear in dilute neutron matter, both in structure and reactions?

What is the density and isospin dependence of the nuclear equation of state?

NUCLEAR THEORY

Nuclear theory is entering a precision era with developments in connecting QCD with nuclear structure, great progress towards achieving a unified description of all nuclei and new developments in reaction theory. Reaching the scientific goals involves new challenges in theory that require sustained computational resources as well as the training of the next generation of researchers in nuclear physics across Europe.

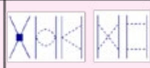
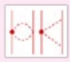
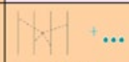
How does the nuclear chart emerge from the underlying interactions?

During the last decade, nuclear structure theory has evolved into a field with a systematic theoretical foundation, with nuclear forces based on QCD and advanced methods to solve the nuclear many-body problem with controlled uncertainties. Effective field theories (EFTs) are

Box 1. Chiral EFT for nuclear forces

The contributions to two-, three- and four-nucleon interactions at successive orders in chiral EFT are shown diagrammatically. The interaction between nucleons (solid lines) is mediated by the exchange of pions (dashed lines), the Goldstone bosons of QCD, which are responsible for the long-range part of strong interactions. The short-range parts of nuclear forces are developed in a general series of contact interactions.

Many-body forces are highlighted including the year they were derived. Three-nucleon (3N) forces, which emerge naturally in EFTs, enter at next-to-next-to-leading order (N²LO). Moreover, EFTs lead to a hierarchy among many-body interactions.

Order	Nucleon-Nucleon (NN)	Three-Nucleon (3N)	Four-Nucleon (4N)
LO			
NLO			
N²LO		 1994/2002	
N³LO		 2011	 2006

playing a guiding role in this process, as they reduce the complexity of the underlying QCD theory to the relevant degrees of freedom in a systematic way (see Box 1). While this was first demonstrated for light nuclei, considerable progress in recent years has highlighted that this approach can be extended towards heavier systems.

The era of nuclear structure physics, where EFTs of the strong interaction provide an exciting link between experimental and theoretical frontiers, has just started. For strong interactions at low energies, chiral EFTs offer a systematic basis for nuclear forces, built on the symmetries of QCD, with controlled expansions of the interactions in the inverse chiral-symmetry breaking scale. Combining EFT with advanced few- and many-body methods opens up a systematic path to investigate nuclear forces and their impact on nuclei and nuclear matter. This provides a link between nuclear structure and matter in stars with the underlying theory, to which it is connected through lattice QCD simulations of few-nucleon systems.

In strongly interacting systems, three-body forces are especially important and have been the target of recent theoretical and experimental work. The calculation of light nuclei required the introduction of three-body forces and they play a key role in universal properties of halo nuclei and their connection to the Efimov effect in ultra-cold atoms. Three-nucleon (3N) forces are a frontier in the physics of nuclei, for shell structure and the evolution to the driplines. Exotic nuclei become increasingly sensitive to 3N forces and other subtle components of nuclear forces, so that experiments with rare-isotope beams provide unique insights into strong interactions. Calculations based on nuclear forces also provide systematic constraints for the properties of nuclear matter in astrophysics. The physics of nuclear forces therefore connects nuclear structure with nuclear astrophysics.

The ongoing exploration of many-body forces is particularly exciting, because at N3LO, 3N and 4N forces are predicted with many new structures. These have never been applied beyond the lightest nuclei and must still pass experimental precision tests. These developments are timely with the establishment of major nuclear physics facilities, which will give great access to the unexplored regions of the nuclear chart.

The electroweak force plays a crucial role in nuclear physics. Gauge symmetry allows the use of the same EFT expansion to derive electroweak operators that are consistent with the strong interaction. Therefore, the couplings in nuclear forces also largely determine electroweak processes, which provide important consistency tests. Two-body currents, also known as meson-exchange currents, have been shown to provide significant contributions to electromagnetic moments and transitions in light nuclei. The exploration of electroweak interactions in nuclei and nuclear matter is therefore emerging as a new area of EFT research.

Achieving a unified description of all nuclei

The exploration of nuclear systems proceeds on many fronts employing a range of theoretical nuclear structure methods. Nuclei exhibit all the features of complex many-body systems as they span from one up to about three hundred nucleons. The individual nucleons interact through the strong and the electromagnetic forces, with intricate details of the interaction driving evolving structures. At the same time, many macroscopic quantities can be understood by concepts similar to those used to describe simple Fermi systems.

A particular challenge is therefore to bridge the gaps between different scales in nuclear physics in order to achieve a unified description.

There are essentially three types of approaches to address the bound, resonant, and continuum properties of all known nuclei as well as the properties of nuclear matter. These are the *ab initio* methods, shell model (SM) approaches, and models based on density functional theory (DFT). These are not systematically connected with each other, but rather represent different levels of phenomenology, approximations and predictive power.

The understanding of few-nucleon systems is critical before extending models also to heavier nuclei. In this sense, the solution of the few-nucleon problem is an important starting point for *ab initio* methods and several approaches are being used to explore and constrain nuclear forces in the few-nucleon sector. At the same time, much progress has been made in the development of many-body methods (such as nuclear lattice simulations, quantum Monte Carlo methods, no-core shell model extensions, coupled-cluster methods, the in-medium similarity renormalization group, and Green's function based methods) with a significantly extended reach towards heavier systems (see Box 2). New methods have been developed and successful benchmarking between different approaches has been performed along chains of isotopes. This is particularly important since *ab initio* methods claim to solve the many-body problem without uncontrolled approximations. Such approaches therefore promise to provide quantified theoretical uncertainties. Results from different approaches should agree with each other when starting from the same interactions.

Currently, several approximations have to be invoked to study heavier nuclei. There are renewed efforts to connect rigorously these global methods with nuclear forces based on chiral EFT.

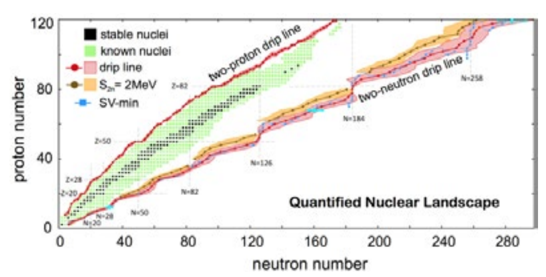


Figure 1. Map of bound even-even nuclei as a function of proton and neutron number Z and N. Drip lines and their uncertainties (red) were obtained by averaging the results of different energy-density functionals.

DFT represents the largest class of models, in terms of applicability on the nuclear chart, see Figure 1. In this approach, the energy of a system is expressed as a functional of the various local or non-local densities in all spin and isospin channels including their derivatives. The present energy density functionals (EDF) have relatively simple forms and are fitted to reproduce global properties such as radii and masses across large regions of the nuclear chart. Statistical methods allow determining the correlations among EDF parameters. However, reliable extrapolations are still challenging, in particular to neutron-rich regions. The current thrust of research in nuclear DFT is in proposing, implementing, and testing new forms of EDF that would allow for systematic expansions in the sense of effective theories so successfully applied to studies of nuclear forces.

DFT can be extended to the time-dependent case (Random Phase Approximation and extensions) and to multi-reference DFT in which broken symmetries are restored. Such extensions of DFT are a valuable tool not only to investigate bulk properties but also for nuclear spectroscopy as well. Ongoing efforts should also be focused on developing functionals that are increasingly accurate, especially concerning the parts of the functional associated with the neutron-proton asymmetry. Another promising direction is the construction of *ab-initio-based* functionals connected to nuclear forces. In general, the connection between DFT and methods based on many-body perturbation theory should be better elucidated (as is envisaged also in other domains such as condensed matter theory).

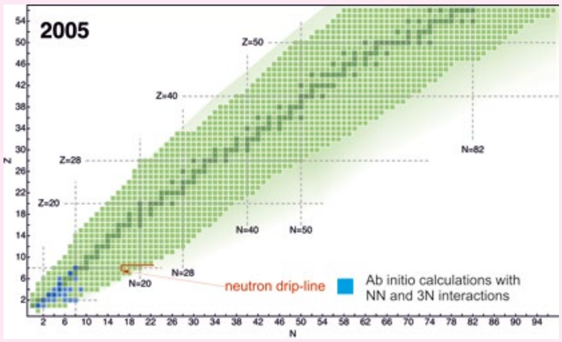
The shell model corresponds to an effective theory for low-energy excitations considering the nucleus as a closed-shell core with additional interacting valence nucleons. The use of effective valence-space Hamiltonians, including the contributions from configurations outside the model space, reduces the computational cost and enables calculation of properties for large regions in the nuclear chart. Large-scale SM calculations have become a well-established approach to microscopically investigate medium- and heavy-mass nuclei whose description requires very large model spaces with many valence nucleons.

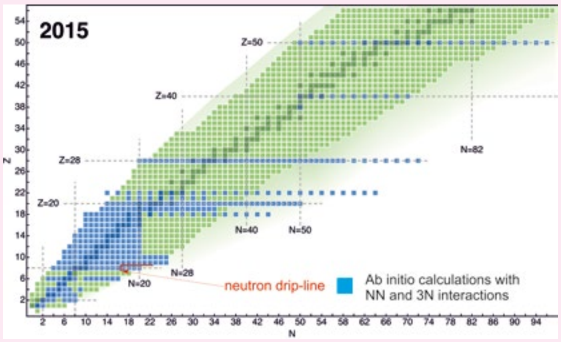
Substantial progress has been made during the last decade in understanding the link between the SM effective Hamiltonian and the underlying nuclear forces. Valence-space Hamiltonians can be derived by means of many-body perturbation theory. It was also recently demonstrated that it is possible to use non-perturbative *ab initio* methods to generate effective interactions for use with SM methods.

Box 2. The reach of *ab initio* methods

In recent years, ab initio computations of nuclei have advanced tremendously. This progress is due to an improved understanding of the strong interaction that binds protons and neutrons into nuclei, the development of new methods to solve the quantum many-body problem, and increasing computer performance. In the early years of ab initio methods progress was approximately linear in the mass number A because the computing power, which increased exponentially according to the Moore's law, was applied to exponentially expensive numerical algorithms. In recent years, however, new generation methods, which exhibit polynomial scaling in A, have dramatically increased the reach. The figures show the chart of nuclei and the reach of ab initio calculations in 2005 (top) and 2015 (bottom). Nuclei for which ab initio calculations exist are highlighted in blue. Note that the figure is for illustrative purposes only, and is based on a non-exhaustive survey of the literature.

These recent developments allow the employment of ab initio many-body methods to perform dedicated tests of nuclear interactions and to answer what input is required to best constrain nuclear forces.





At the other extreme of nuclear models are the macroscopic models based on dynamical symmetries, characterised by definite underlying algebraic structures, which have long provided predictions for the properties of nuclei out of reach of microscopic models. Linking symmetry-based descriptions to microscopic theory remains a challenge.

Towards consistent reaction theory

Much of our understanding of nuclei comes from experiments involving nuclear reactions. A proper description of nuclear reactions requires the combination of suitable structure models with an adequate understanding of the reaction mechanism. In addition to their use as a tool to extract structure information, reaction studies have also served to reveal interesting dynamical features such as, for example, those derived from the coupling to the breakup channels in reactions involving weakly bound nuclei. In order to properly handle new observables and exotic structures, developments and extensions must be made, both in the treatment of the reaction dynamics as well as on their nuclear structure inputs.

The field has realised several advances, including applications of the Faddeev formalism to nuclear reactions induced by light weakly-bound projectiles; successful extensions of continuum coupled-channels methods to four-body reactions involving three-body projectiles such as Borromean nuclei; a more realistic description of the clusters in few-body reaction formalisms, either by including possible collective excitations of these clusters on equal footing with the single-particle excitations (see Figure 2) or by incorporating their microscopic structure (e.g., via the RGM method); improvements of transfer reactions formalisms (e.g., incorporation of non-local interactions, multi-nucleon transfer) and a variety of promising extensions of ab initio methods to nuclear reactions.

In addition to these novel developments, there has been an intensive activity aimed at re-examining and, when appropriate, upgrading, existing methods, motivated by the new experimental demands and enhanced computational capabilities, thus overcoming constraining approximations of their original formulations. These include the revival of microscopic two-nucleon transfer, inclusive breakup models, and time-dependent Hartree-Fock approaches to fission.

Developments in reaction theory must consider both, the adequate treatment of the reaction dynamics as well as the reliability of the underlying structure models and the effective interactions. With this general scope, several developments would be advisable for the forthcoming years: improvements in effective potentials and better understanding of the need of non-local potentials, developments of dispersive optical model potentials; a more extensive use of microscopic inputs (e.g., transition densities, microscopic overlaps) in reactions calculations; a more accurate treatment of quasi-free breakup reactions; theories for charge-exchange reactions (including double-charge exchange) with a potential use as a tool to extract information on the neutrino-less double-beta decay matrix elements; development of fully quantum-mechanical models for incomplete fusion; further extensions of *ab initio* methods to reactions. Finally, it is desirable to establish an interface of the output of direct reaction codes with the event generators required by the simulation codes used to describe complex detector arrays. This will allow comparing directly the experimental evidence of fragment correlations, in a given setup, with theoretical results.

Computational challenges to reach the scientific goals of nuclear physics

Computational methods play a very important role in nuclear physics research and are already fundamental to the success of key components of present and future experimental programmes.

In nuclear theory the research methodology is a combination of both analytical techniques and medium-sized or large-scale computations. In fact, high-performance computing is a critical ingredient to reach the scientific goals of nuclear physics. It allows the tackling of questions that were previously thought to be intractable, and computer-based models enable the numerical exploration of systems that are still inaccessible to experiments.

Recent achievements in DFT (see Figure 1), *ab initio* methods (see Box 2), large-scale SM calculations

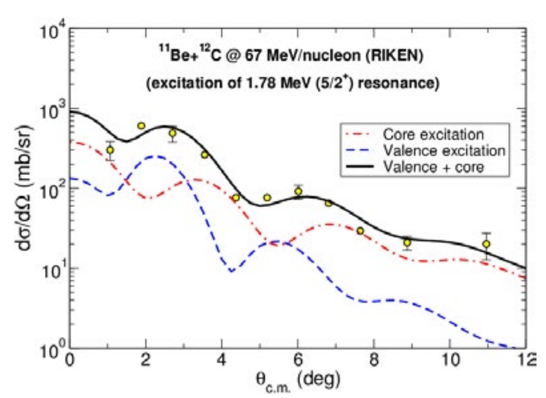


Figure 2. Interplay of valence (halo) versus core excitation mechanism in the resonant breakup of the halo nucleus ^{11}Be on a carbon target in comparison with RIKEN experimental data.

and reaction modelling are clear examples of current successes for high-performance computing in nuclear physics. This need will continue to increase in the coming decade. Nuclear physics is one of the research fields that will benefit the most from increased efforts to tackle computational challenges through collaborations between different research groups, computer scientists and applied mathematicians. Future investments in computational resources are obviously essential. However, the trend with rapidly evolving hardware architectures requires a parallel development of research software and algorithms. This demand calls for the training of a very diverse workforce that can utilise these new resources and push the frontiers of nuclear theory.

The precision era of nuclear theory

Uncertainty quantification is an important topic in science. In recent years, the need for uncertainty estimates in theoretical calculations has started to be recognised in the nuclear physics community, in particular when claiming predictive power. Reliable theoretical errors make it possible to infer the significance of a disagreement between experiment and theory. The task of assigning uncertainties to theoretical calculations of strongly interacting systems is challenging. An important source of uncertainty in calculated observables arises from the fact that parameters, e.g., the low-energy constants in chiral EFT or those appearing in effective interactions or EDFs, are usually determined by fits to the experimental data. The statistical errors associated with this procedure can be calculated by different methods as exemplified in Figure 3.

A statistical analysis is also a powerful tool to establish correlations between different parameters and determine weakly and strongly constrained parameters. However, in addition to statistical errors, systematic errors arising from the approximate character of physical models or missing aspects of the models have to be considered. The calculation of systematic errors is very difficult and there is no unique strategy for their estimation. However, systematic approaches such as EFT provide hope of also delivering quantified systematic uncertainties. Within this context, it may also be useful to compare the prediction of different models or significantly reduce the statistical errors to acquire information on the quality of the model from the disagreement between theory and experiment. Recent works have been published employing statistical methods and scientific computing to determine the independence of model parameters, parameter uncertainties, and the errors of calculated observables.

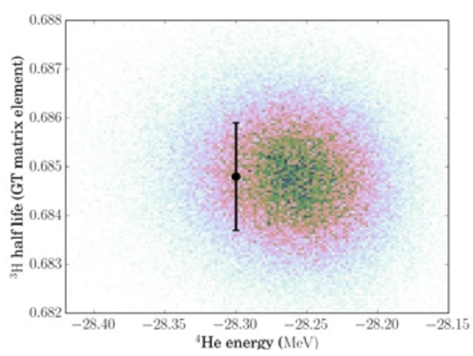


Figure 3. *Ab initio* results for the triton half-life (vertical axis) versus ^{4}He energy (horizontal). These results demonstrate the propagation of statistical theoretical errors to few-nucleon observables. The two-dimensional histogram corresponds to 10^5 computations of the A = 3, 4 systems with statistically sampled low-energy constants in chiral EFT. The marker with error bars represents experiment.

New developments in this field will have an impact on our understanding of the structure of nuclei and their reactions. They will be helpful to identify new relevant experiments by revealing what experimental data are crucial to better constrain nuclear theory and to provide information on systems or conditions that are not accessible by experiments.

Nuclear physics also plays a vital role in the larger context of fundamental science. Nuclear physics input is required for many important questions in particle-, astro-, and atomic-physics research and in searches for beyond Standard Model physics. At this research frontier, nuclear physics is expected to provide precise measurements or theoretical predictions for relevant observables such as cross sections, masses, or nuclear matrix elements. The ability to associate reliable uncertainties with such predictions is absolutely critical for progress and to reveal the existence of new physics.

Open issues and perspectives

Continued efforts to increase the precision and to extend advanced few- and many-body methods to new regions of the nuclear chart, into medium-mass regions away from closed shells and including continuum degrees of freedom are required.

Focused research on constructing improved nuclear EDF that would allow for a precise description of nuclear properties across the nuclear chart, including the spin and isospin channels, restored symmetries, and spectroscopic data is required.

Powerful developments of large-scale SM methods are needed; exploring new regions and valence spaces, advancing novel derivations of effective Hamiltonians and consistent operators and including the coupling with the continuum for weakly bound nuclei.

Increased efforts are needed to examine the validity of existing reaction formalisms, extend them to new exotic nuclei and observables, and improve structure inputs. Benchmark calculations of existing reaction models are advised to better establish their limits of validity and identify their limitations.

Sustained progress in nuclear theory requires developing new methods and new ideas supported by employing the most advanced computational tools, access to high-performance computational facilities and by benefiting from increased efforts in training young talent. The successful TALENT graduate training initiative should be supported on a continuous basis.

NUCLEAR STRUCTURE

Current nuclear structure research is driven by several fundamental questions: Which are the most important few-body data to constrain nuclear forces? To what extent can the nucleus be described in terms of nuclear shells and how does shell structure evolve across the nuclear landscape? How can we describe nuclear excitations? What shapes can a nucleus adopt? Do neutron halos and neutron skins exist all over the nuclear chart? What are the origins of clustering in dilute neutron matter? Are there nuclear systems which can be described statistically or present chaotic behaviour?

Which novel few-body data will constrain our understanding of nuclear forces?

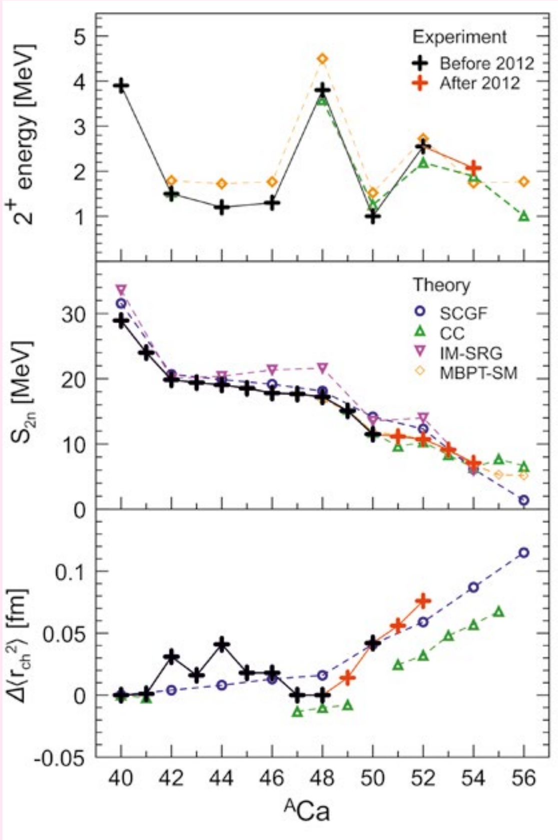
Few-body systems continue to provide important observables for testing and constraining nuclear forces and electroweak interactions at low energies. Future topics of interest include explorations of neutron-rich resonances ranging to the extremes of isospin with pure few-neutron systems, novel studies of electroweak reactions with consistent operators, as well as the extension to strangeness with precision experiments for hypernuclei.

Hypernuclei

Understanding of the nuclear force can be extended to the flavoured-SU(3) symmetry by studying hypernuclei, nuclei with bound hyperon(s) (baryons with strange quarks where Λ (usd) is the lightest). Hyperons in hypernuclei can

Box 3. Structure of Ca isotopes

Standard magic numbers, well established for stable nuclei, fade away in neutron-rich systems where new ones may appear. How do we determine their location? A shell closure cannot be established from a single experimental signature but rather has to emerge from the concurrence of several features, e.g. in energies of the lowest 2^+ excited state, two-nucleon separation energies and charge radii isotopic shifts. Hence, different experiments are typically necessary to assess the evolution of magic numbers, as testified by recent studies of neutron-rich calcium isotopes. Penning-trap measurements at TRIUMF and ISOLDE have extended our knowledge of nuclear masses up to ^{54}Ca (central panel) and pointed to the appearance of a new magic number at *N*=32. More recently, charge radii obtained via laser spectroscopy at ISOLDE (lower panel) weakened this conclusion. In parallel, the measurement of the lowest 2^+ excited state in ^{54}Ca at RIKEN (upper panel) has opened the same debate on *N*=34. Ab initio calculations (coloured curves) have started to access medium-mass isotopic chains systematically. Comparisons between these calculations and current and future experiments in the region, e.g. up to ^{56}Ca, will help unveil how such magic numbers emerge from underlying complex nucleon dynamics.



be used as probes of the inside core of nuclei since the hyperon is not subject to the Pauli principle. Hypernuclei close to stability were studied mainly using reactions of meson- and electron-beams. A recent hypernuclei spectroscopic study of $^{3}_{\Lambda}$H is discussed in chapter 1. These studies open a new degree of freedom related to strangeness, which could be combined with exotic nuclei. For instance few-body systems such as 2n+Λ remain to be explained by first principles. These studies are also appealing for future developments.

Resonances in neutron-rich nuclei

Unbound systems of extreme isospin up to pure few-neutron resonances provide novel tests of neutron-neutron interactions and constrain the isospin T = 3/2 component of three-nucleon forces, which is not probed in nucleon-deuteron scattering. The resonance energies and widths of the unbound systems can be assessed by experiments using intense radioactive beams and employing invariant-mass and missing-mass spectroscopy. On the theoretical side, neutron-rich resonances are extremely challenging, as they require the understanding of nuclear forces and of the continuum.

The properties of unbound systems made only of neutrons are related to three-neutron forces. Testing and constraining three-neutron forces is in turn crucial for neutron-rich nuclei and the equation of state of neutron-rich matter, which is key for understanding and predicting properties of neutron stars. In addition, few-neutron resonances are also considered a milestone calculation in lattice QCD.

Electroweak reactions

Electromagnetic and weak interactions play a crucial role in nuclear physics. On the theoretical side, gauge symmetry allows the use of the same effective field theory to derive electroweak operators that are consistent with the strong interaction. As a result, the couplings in nuclear forces also determine electroweak processes. This provides important consistency tests for few-body experiments. For electro-magnetic reactions, two-body currents were derived recently and shown to provide significant contributions to electromagnetic processes in few-nucleon systems, e.g., to magnetic moments and B(M1) and B(E2) transitions.

The exploration of electroweak interactions in nuclei is therefore emerging as a new area of effective field theory research. Experimentally, this opens up exciting opportunities for precision tests with electroweak reactions (see e.g. the S-DALINAC).

Electron nucleus scattering experiments have greatly contributed to shed light on the "spectroscopic factor puzzle" (see Box 6), as well as on the long-standing and elusive issue of nucleon-nucleon correlations. More experiments will be needed to acquire additional information, which is indispensable for searches of neutrino oscillations (see Ch.5).

How does shell structure evolve across the nuclear landscape?

The shell model describes the structure of nuclei assuming the nearly independent motion of a few (so-called valence) nucleons in a mean potential generated by all other nucleons (the core). In this framework a few nuclei are interpreted as closed-shell nuclei with magic numbers of nucleons. Their sequence, well known for stable nuclei, is a fingerprint of the properties of the nuclear force. However, it is not fully clear how magic numbers evolve as a function of the neutron-to-proton ratio. Different facets of nuclear forces have been revealed to play a role but despite continuous efforts, this evolution is far from being established.

Exploration towards the drip lines

Basic observables (energy of first excited state, masses and beta-decay half-lives) are used to explore nuclear structure in new regions of the nuclear landscape. This information is obtained with radioactive beams of ISOL and in-flight types, as illustrated for the case of the Calcium isotopic chain along which new subshell closures at N=32,34 are under debate (see Box 3). The exploration of new regions of the nuclear landscape has been and will be a world-leading programme in Europe and in the future the regions of possible closed-(sub) shell nuclei ^{48}S, ^{60}Ca and ^{100}Sn will be investigated. The use of decay and mass spectrometry at FAIR will enable to explore the very neutron-rich nuclei with Z larger than 60 beyond and above ^{132}Sn and ^{208}Pb to be explored. Measurement of the first accessible observables (e.g. 2^+ energy, lifetime) should be complemented by more detailed investigations requiring intense low-energy beams.

In recent years, several physics programmes using European detector arrays were initiated in international collaborations at RIKEN. They led to worldwide unique physics results concerning the r-process nuclei around doubly magic ^{78}Ni and the spectroscopy of nuclei at and beyond the drip line. The spin-orientation obtained in two-step projectile fragmentation allowed nuclear moment studies of microsecond isomeric states in very exotic nuclei. These activities should continue in the coming years.

Comprehensive spectroscopy

Particle spectroscopy of bound and unbound states from nucleon transfer reactions offer information on the quantum numbers of the populated states and their nature in terms of neutron or proton excitations. Transition probabilities from lifetime measurements or Coulomb excitation, as well as electric and magnetic moments, add crucial information on the wave functions of individual states.

Low-energy nucleon transfer reactions enable studies of the nature of ground and excited states as a function of isospin. The medium and heavy mass regions should be uniquely accessed at new generation ISOL facilities producing intense radioactive ion beams at around 10 MeV/A (from fission of ^{238}U at rates larger than 10^{12} f/s). Such studies would require an efficient combination of high-granularity particle detection and high-resolution gamma spectrometers, as illustrated in the proof-of-principle case shown in Figure 4. The evolution of the hole and single-particle states along the tin isotopes will be studied near and beyond ^{132}Sn and in the region of ^{78}Ni.

Laser spectroscopic techniques are planned to be used for nuclear moment studies in these regions, e.g. at ISOLDE and SPIRAL2/DESIR while techniques allowing spin/parity determination of both ground and excited states are presently being developed at ALTO. Nuclear moments, spins and charge radii of ground and excited nuclear states provide key information on the nuclear wave function. Charge radii in isotopic chains also give also indirectly insight into the neutron distribution. Electric quadrupole moments are the closest experimental approach to determine nuclear shape. Magnetic dipole

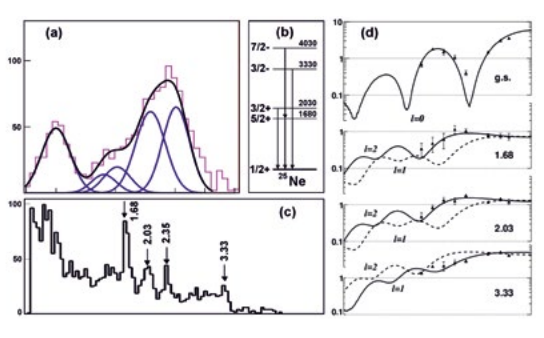


Figure 4. Particle and gamma spectroscopy of ^{25}Ne from the one-neutron transfer ^{24}Ne*(d,p)*^{25}Ne at 10.6 MeV/nucleon at GANIL/ SPIRAL1. (a) Excitation energy (counts / 190 keV) fitted with (b) observed levels in ^{25}Ne defined by (c) gamma-ray energy (counts / 40 keV), resulting in (d) differential cross sections (mb/sr *vs* laboratory angle).

moments, considered as fingerprints for single-particle states, can provide information on the interplay between single-particle and collective degrees of freedom.

Depending on the location in the nuclear chart, strong correlations redistributing protons and neutrons across closed shells may result in appreciable effects. This can give rise to unexpectedly low-lying states, which can lead to configuration mixing and shape coexisting structures.

Important cases to study will be the region of neutron rich iron and chromium isotopes towards ^{60}Ca, where a so-called Island of Inversion has been evidenced but not completely characterised, neutron-rich nickel isotopes beyond N=50 and tin isotopes beyond N=82.

The structure of nuclei with N=Z is expected to exhibit unique features due to the reinforced coherent contribution of protons and neutrons at the Fermi energy. In particular, the role of neutron-proton T=0 pairing in the region of ^{100}Sn is to be understood. Properties of mirror systems will contribute further to the study of isospin symmetry. SPIRAL2/S3 and MARA are some of the key facilities for investigating proton-neutron interactions along the N=Z line both for ground and excited states. In addition, "deuteron" transfer cross sections should open new insight in the study of neutron-proton Cooper pairs.

The development of new techniques using isomeric beams to measure pickup or stripping from short lived to very short lived states (from μs to ps) will provide a new dimension in nuclear structure.

Recent developments of nuclear moment studies of excited states with picosecond lifetimes, populated in Coulomb excitation, can provide high-accuracy results using well defined charge states (H-like or alkali-like). This approach could provide information on the interplay between single-particle and collective properties of light exotic nuclei.

Single- and few-nucleon transfer reactions as a mean for spin-orientation are presently being investigated and might provide a way for nuclear moment studies of isomeric states with post-accelerated ISOL beams.

Heavy and superheavy elements

The stability and existence of superheavy elements derive from the shell correction energy. Understanding the structure and stability of heavy elements therefore requires the study of the underlying shell structure. The question of the next magic numbers beyond Z=82 for protons and N=126 for neutrons, namely the location and extension of the fabled "Island of Stability" of nuclei with possibly very long half-lives is still open. The predicted shell-correction energy (which can be linked to the level density and degeneracy of the single-particle states at these particle numbers) varies smoothly over a wide range of nucleon number but depends on the theoretical approach used. It has been shown that the stability of heavy nuclei is also influenced by *deformed* shell closures, particularly at Z=100, 108 and N=152, 162.

The vast majority of level assignments are derived from α or β-decay spectroscopy, sometimes combined with coincident γ-ray or conversion-electron data. A few reference points around Cm-Cf were established by transfer reaction data. In the coming years, focus should be given to direct mass and nuclear spin measurements, which are extremely rare in the heaviest elements. Optical methods, previously restricted to macroscopic samples, are advancing to access nuclei produced on-line. Current spin assignments can thus be confirmed, providing the required anchor points for decay spectroscopic data. These studies demand the highest-intensity stable beams, as the nuclei of interest cannot be produced in any other way. The successful resonant ionisation spectroscopy of nobelium performed at GSI paves the way for detailed spectroscopy of nobelium and heavier nuclei.

Knowledge on high-spin and isomeric states from in-beam studies complements information from decay experiments and is obtained by coupling large arrays of germanium detectors to efficient recoil separators. Technical advances have pushed the spectroscopic limit to Z=104, facilitating in-beam studies at the 10 nb level. In-beam studies yield information on the moments of inertia (and indirectly the pairing interaction), alignment effects, deformation and stability as a function of excitation energy and spin. Future studies require further development in γ ray and conversion-electron spectroscopy, in conjunction with improved and new recoil separators (e.g. S3, MARA) designed for higher efficiencies and greater background suppression to push the spectroscopic limit even further.

Detailed spectroscopic studies can constrain nuclear structure theory, but only indirectly shed light on the high-Z limit of the nuclear chart (Figure 5). The heaviest element currently known has Z=118. Thus to directly explore the limits of nuclear stability, a priority in the coming years will be production of new elements, firstly those with Z=119 and 120. Such experiments should be guided by refined nuclear reaction and structure theory, and represent a main driving force for the development of stable beams with the highest possible intensities. The possibility to directly determine Z of the heaviest known nuclei was demonstrated recently in pioneering studies of the element 115 decay chains with the TASISpec setup at GSI Darmstadt and is of high priority, as is that for A determination, for which complementary instrumentation is being built.

Indirect evidence is emerging on the importance of electron capture decay in the heaviest elements, a decay mode that cannot currently be directly detected. Promising results have also been obtained by the analysis of reaction time distributions, pointing towards to production of Z=120,124 elements.

Novel techniques such as calorimeter-based detectors (already established in other fields) should thus be developed. Chemical methods can serve as Z-separators providing ideally clean samples for further studies. The coupling of chemistry apparatus to recoil separators has allowed Fl (Z=114) to be reached. Faster techniques for studying heavier elements are currently being developed. Chemical studies also probe the influence of relativistic effects caused by the high Z. The volatility and reactivity of single atoms and molecules can be studied. Novel approaches will also allow measuring the stability of chemical compounds, broadening the range of experimentally accessible observables. Technical advances such as optical methods, yield information on atomic level schemes or the first ionisation potential of elements produced at higher rates.

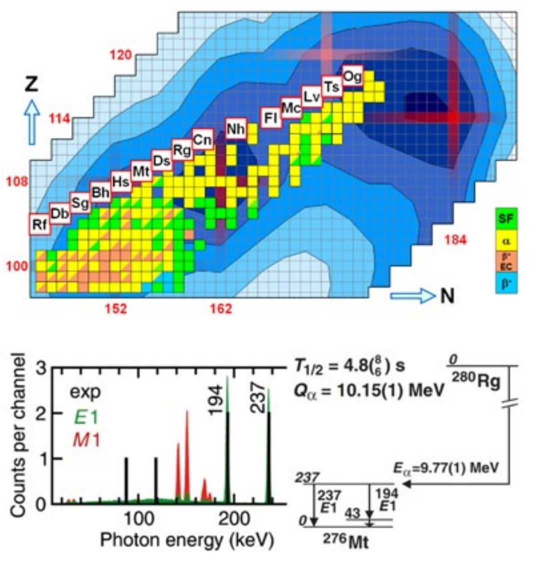


Figure 5 (top) The chart of nuclides in the region of the heaviest elements. The blue contours are calculated shell correction energies in MeV according to a macroscopic-microscopic model. The "island of stability" is located near Z=114 and N=184, indicated in red. The magic numbers Z=120 / N=172 as they alternatively follow from relativistic mean field model calculations are also indicated, along with the deformed shell closures at N=152,162 and Z=100,108. Experimentally observed nuclei are indicated as coloured boxes. (Bottom left): Experimental photon spectrum (black) observed in coincidence with α particles assigned to ^{280}Rg in the study of element 115 decay chains from the ^{48}Ca+^{243}Am reaction measured at GSI; simulated spectra for the level scheme are shown with the assumed E1 (M1) transitions in green (red). (Bottom right) Proposed level scheme, based on the combined data from experiment and simulations.

How complex are nuclear excitations? Coupling between nucleons and core-excitations

The interplay between single particle excitations and collective responses of the nucleus generates a multifaceted scenario of nuclear excitations, which can be studied in their simplest form in systems made of one valence particle and a doubly magic core. Here, long range correlations, such as couplings between particles and excitations of the core (phonons in particular) are major sources of partial occupancies of nucleonic orbitals (as evidenced by knock out and transfer reactions), they are doorways to the damping of resonance excitations and were also found to impact the Gamow Teller strength function in the β-decay of closed-shell systems. Archetypal of these phenomena are ^{49}Ca and ^{133}Sb: γ-spectroscopy studies at LNL and ILL have shown that their valence neutron and proton couple to both collective and non-collective excitations of the ^{48}Ca and ^{132}Sn cores, resulting in fast changes of the wave function composition with spin. Coulomb excitation and transfer studies of odd-Cu/Co isotopes (one proton from the Ni core) performed at ISOLDE, LNL etc., across N=40, have also shown how the robustness of semi-magic shell closure, moving towards exotic regions, can be monitored through studying the properties of particle-core coupled states, in strong complementarity with spectroscopy studies of single-particle states. These isotopes are a natural forefront for *ab-initio* nuclear structure theory that aims at investigating the spectral function for nucleon attachment and removal in large semi-magic isotopic chains. Data around doubly magic (^{132}Sn, ^{78}Ni, ^{100}Sn) and semi-magic shell closure (Ca, Ni, Sn) will therefore be pivotal to further improve our knowledge of nuclear interactions.

From a broader perspective, the emergence of simple and repetitive patterns in the excitation energy and gamma-decay spectra along isotopic chains, e.g., in terms of competition between magnetic and electric transitions, can be used to trace the evolution of the system in the energy-spin-isospin phase space. By profiting from recent progress in isotopic identification achieved in GANIL, both prompt and delayed gamma spectroscopy becomes possible for hundreds of neutron-rich nuclei from a single fissioning system. AGATA and EXOGAM, as well as new setups under development at the intense neutron-beam facility at ILL, will be the workhorses of this field.

Giant Resonances

Giant Resonances are an extreme manifestation of collective excitations, involving a large fraction of constituent nucleons. They provide information on bulk properties of nuclei and their measurement in exotic systems is extremely challenging and limited so far to a handful of cases. The full isoscalar and isovector responses (protons vibrating in phase/out of phase with neutrons) have started to be investigated with innovative techniques, like the MAYA active target setup at GANIL, and the R^3B-LAND setup at GSI. This will allow a systematic study of key quantities, such as compressibility and its impact on the nuclear equation of state of neutron-rich matter (see section on the Nuclear Equation of State). Owing to their complex nature and their influence on reaction rates in the astrophysical r-process, collective excitation modes are under intense scrutiny in a number of stable and exotic systems, by various experimental techniques.

The problem of collectivity in spin, spin-isospin modes is also very crucial. The quenching of M1 and Gamow-Teller decays is of paramount importance in astrophysics, β-decay and double-β decay studies, and information over wide range of masses and deformations is expected in coming years. Low-energy isovector excitations with mixed proton-neutron symmetry will also be extensively investigated in exotic systems, where they are very sensitive to the effective restoring forces between protons and neutrons in the valence shell. In stable systems, these features will be ideally investigated at ELI-NP, together with a variety of elementary collective excitations: quadrupole shape vibrations, double scissors mode, rotational states built on the scissors mode, the M2 twist mode, spherical/deformed octupole vibrations, as well as hexadecupole vibrations and Pygmy (see Box 4).

What shape can nuclei take?

The shape is one of the most intriguing properties of the nucleus. Spherical shapes are most natural in the vicinity of double shell closures. In the regions lying away from doubly magic nuclei different nuclear shapes, with dominance of quadrupole symmetric forms, compete and may coexist in the same nucleus at low excitation energy. In even-even systems, fingerprints of shape coexistence are low-lying 0^+ excited states associated with deformations different from the ground state. A systematic search for such states from two-nucleon transfer and/or conversion electrons is particularly relevant in regions where configuration coexistence at low-energy is expected or partially evidenced.

Spectacular progress has been made in studying shape coexistence in unstable Zn/Ge, Si/Mg, Zr/Sr/Rb/Kr, Po/Pb/Hg and Ra/Rn isotopes. Various experimental probes, e.g., γ-ray and conversion-electron spectroscopy, Coulomb excitation, lifetime measurements and laser spectroscopy, have been used with both stable and radioactive ion beams (for example at JYFL and ISOLDE). Notable examples are ^{32}Mg, ^{79}Zn, ^{80}Ge $^{72-76}$Kr, $^{96-98}$Sr and ^{182}Hg, studied at ISOLDE, ALTO and SPIRAL1. This encourages further detailed studies of shape coexistence far from the stability, aiming at a mapping of this phenomenon across the nuclear chart.

A peculiar manifestation of the coexistence of shapes are shape isomers, arising from the existence of additional deep local minima in the nuclear potential energy, calculated as a function of shape parameters. The most known

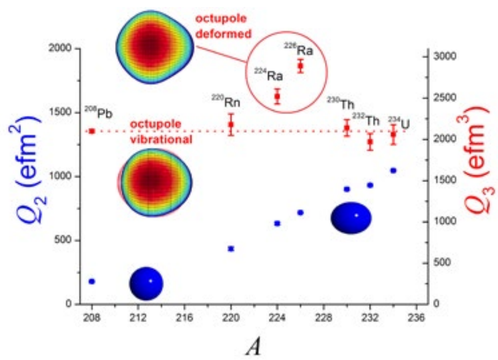
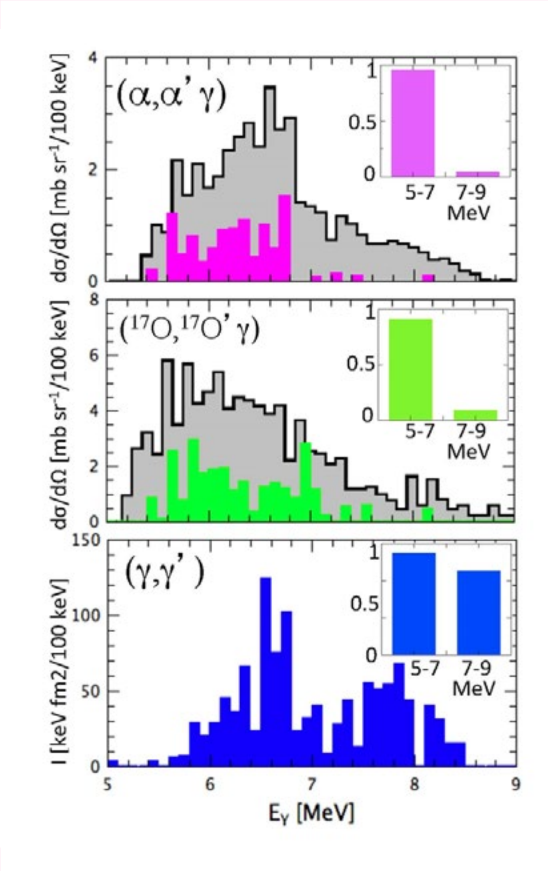


Figure 6. The evolution of shapes in the A > 220 nuclei measured at ISOLDE is well described by quadrupole and octupole moments. While ^{220}Rn shows an octupole vibrational character, similar to ^{208}Pb and heavier Th and U systems, ^{224,226}Ra give evidence for static octupole deformation in the intrinsic frame

Box 4. Pygmy Resonances

In neutron-rich systems, the neutron excess is expected to form a skin, often assumed to oscillate outside the proton-neutron core: this results in a concentration of E1 strength in the region around the particle binding energy (< 10 MeV) - the Pygmy Dipole Resonance. Experiments are ongoing for few exotic nuclei above separation-energy threshold, using advanced and complex setups at fragmentation facilities, while stable systems, below threshold, have been largely investigated by different probes – from photons, high energy protons and alphas and heavy ions at intermediate energies. A quite complex nature of pygmy states has been evidenced, as in the case of ^{124}Sn where isoscalar and isovector states seem to co-exist in the same energy region, and the character of these excitations appears to be hybrid, with mixture of compressional or non-collective character.

New experiments are envisaged to better clarify the features of the low-lying dipole strength with neutron excess and the existence of pygmy states of other multipolarities, E2 in particular. At ISOL facilities, inelastic scattering at 10-15 MeV/nucleon in inverse kinematics will shed light on the nature of the pygmy resonance below particle threshold, while exclusive measurements based on the detection of high resolution γ rays and particle decay at intense gamma-beam facilities, such as ELI-NP, will pin down the fine structure of the entire resonance response in stable systems, shedding light on damping mechanisms.



γ-decay spectra from the pygmy resonance in ^{124}Sn, as measured with α scattering at 34 MeV/A (top, KVI data), heavy ion at 20 MeV/nucleon (middle, AGATA at LNL) and γ scattering (bottom, Darmstadt data). Coloured histograms give the strength resolved in individual transitions, with energy-integrated relative intensities (insets).

manifestation of shape isomers are fission isomers in actinides, however, this phenomenon is predicted in many regions of the nuclear chart, based on microscopic-macroscopic approaches. For example in the neutron rich Ni isotopes, these predictions are strongly supported by state of the art shell model calculations, encouraging future investigation at radioactive beams facilities.

New (dynamical) symmetries are also being searched for in nuclear matter. The description of higher-order deformation of nuclei, resulting from octupole, or hexadecapole symmetries, remains an experimental challenge. Recently, major progress has been obtained in the investigations of octupole correlations in Rn and Ra chains (see Figure 6): Coulomb excitation experiments at ISOLDE have given firm evidence of static octupole deformation in ^{224,226}Ra. This helps to constrain candidates for experimental studies of the atomic electric-dipole moment (EDM) that would indicate CP violation and, in consequence, the existence of physics beyond the standard model. Octupole correlations still remain to be understood in the Xe, Te and Ba isotopes both close to ^{100}Sn and beyond N=82, where theory predicts extended region of deformation. From a broader perspective, the understanding of the octupole degree of freedom in nuclear matter is of general interest as it can also be used for the description of clusters in nuclei, evaporation of heavy fragments and asymmetric fission processes.

Superdeformed (SD) nuclear shapes are a major facet of nuclear structure. SD states become yrast at high spin, but their decay to normal deformation proceeds through highly excited states in the quasi-continuum. This transition from an ordered to a chaotic and back to an ordered regime remains to be fully understood. In general, the properties of the warm rotation, both in normal and SD systems, need to be further detailed, and can be used as a tool to pin down the onset of chaoticity in terms of fragmentation of rotational γ-ray strength with increasing excitation energy. In light nuclei, SD states can be interpreted as multiparticle-multihole excitations across spherical shell gaps. The very first AGATA experiment at LNL provided firm experimental evidence for (triaxial) superdeformation in ^{42}Ca, see Figure 7.

Triaxial nuclei also remain a challenge to understand particularly in the rare earth region where rotational structures are observed to ultra-high spin (I>60ħ). A consistent picture between experiment and theory of the shape, spin and excitation energy of these bands requires further experiments with high efficiency gamma-ray spectrometers (e.g. AGATA).

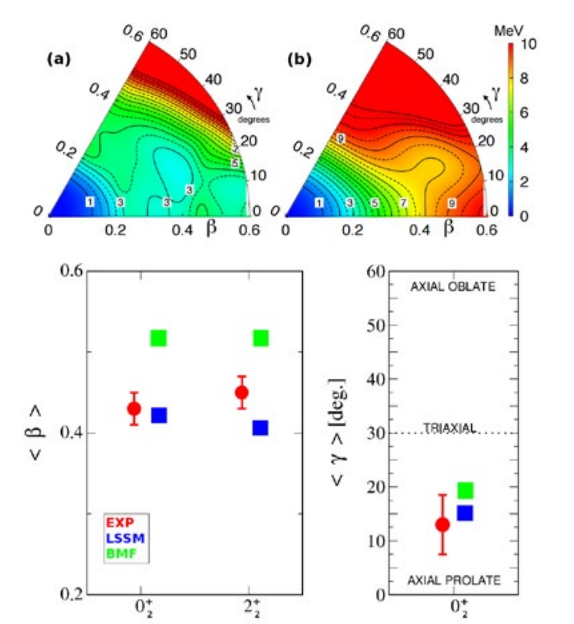


Figure 7. Coulomb excitation of ^{42}Ca was used to measure for the first time static quadrupole moments of the superdeformed states and to extract the quadrupole shape parameters (β,γ) (top figure). The experimental results, providing firm evidence for coexistence of spherical and (slightly triaxial) superdeformed structures in ^{42}Ca, are supported by state-of-the-art shell model (panel a; blue squares) and beyond mean field (panel b; green squares) calculations. They bring decisive information about shape evolution close to doubly-magic nuclei. The potential of Coulomb excitation as a tool to study superdeformation has been demonstrated for the first time and opens up new vistas for future studies at next generation RIB facilities.

Even more elongated, so-called hyperdeformed (HD) shapes are predicted in neutron-rich nuclei, but direct evidence still remains to be found in reactions populating nuclei at the highest possible spin. Nuclei are furthermore expected to undergo a Jacobi shape transition under such extreme conditions. The searches for new regions of SD and HD in moderately neutron-rich isotopes will have to make use of fusion-evaporation reactions induced by intense neutron-rich radioactive beams which will be provided by the ISOL facilities in the future. Advanced implementation of highly efficient γ-ray arrays, such as AGATA, that can collect high multiplicity data, used often with specific ancillary detectors and separators, will be key instruments for these investigations.

How do neutron halos and skins evolve across the nuclear chart?

Halo nuclei exhibit, in some of their states, a wave function which extends well beyond the core of the nucleus. They represent a unique quantum phenomenon in nuclear systems. A rule of thumb defines a halo when the nucleon probability in the region forbidden by classical mechanics exceeds 50%. P-wave neutron halos have recently been claimed to appear in very neutron-rich Ne and Mg isotopes although this is not yet firmly proven and should be further explored through exclusive measurements. Halos in short-lived excited states still have to be found. For medium mass nuclei, the appearance of a halo is controversial and today no data supports the existence of the phenomenon, the heaviest halo nucleus claimed so far is ^{31}Ne. Neutron skins, corresponding to a neutron density distribution larger than the proton one at the surface of the nucleus, have triggered numerous studies and efforts. In stable nuclei they have been investigated using various probes and skins thicker than 0.5 fm were observed in light neutron-rich nuclei. A systematic study of neutron skins would open the way to map out its evolution and the occurrence of low-density neutron matter as a function of proton number.

To reach the most neutron-rich in which halos and thick neutron skins could be observed, probes sensitive to low production rates should be further developed. A systematic study of the evolution of the neutron skin thickness along isotopic chains (for example the $^{126\text{-}138}$Sn isotopes) would be possible via indirect neutron and proton-removal cross sections at intermediate energies. This indirect method has the advantage of allowing a first estimate of the neutron skin thickness down to low intensities of few tens of particles per second, although it would require benchmarks to quantify the reaction-model uncertainties. The use of low-energy antiprotons produced at CERN to populate antiprotonic atoms with unstable nuclei is being considered and should be a way to produce very neutron-rich exotic nuclei. This will give access to undiscovered regions of the nuclear chart where it will be possible to examine the existence of halos and neutron skins.

Observables Deduced quantity	**Reactions**	**I [s^{-1}] L [$cm^{-2}s^{-1}$]**
r.m.s. matter radii	*(p,p) at small q*	I =10^4 (light)
Matter density with 3 parameters ρ_m	*(p,p) 2nd min.*	I = 10^{5-6} (medium-heavy)
r.m.s. charge radii	*(e,e) at small q*	L: 10^{24} (light)
Charge density with 2 parameters ρ_{ch}	*(e,e) first min.*	10^{24-28} (light-heavy)
Charge density with 3 parameters ρ_{ch}	*(e,e) 2nd min.*	10^{26-29} (medium-heavy)
Neutron skin from ρ_m and ρ_{ch}	(p,p) and (e,e)	*(p,p)* : I=10^6/s e: L=10^{28} 10^{29}

Table 1. Accessible information from proton and electron elastic scattering off nuclei for fixed target kinematics for typical intensities I and luminosities L, respectively.

An ultimate characterisation of new halos and thick neutron skins throughout the nuclear chart would require the ability to measure accurately the density distributions of both protons and neutrons. Our basic knowledge on the nuclear charge distributions was established on the stable nuclei using electron elastic scattering (indeed at 400-800 MeV the spatial resolution is about 0.5 fm).

Robust insight into the nuclear matter distribution can be obtained by proton elastic scattering. The nuclear interaction is sensitive to both the neutron and proton density distributions. By use of density and energy dependent microscopic potentials to calculate the *(p,p)* cross sections, matter density distributions can be extracted by comparison between calculations and data. Provided the proton distributions are known from *(e,e)*, the neutron densities can be inferred. Sensitivities up to three-parameter proton and neutron distributions, i.e. beyond the radius and diffusiveness, are realistic with unstable ions. A complete picture of nucleon distributions inside a nucleus can be achieved by combining *(e,e)* and *(p,p)* scattering in different momentum transfer regimes.

Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced. As illustrated in Table 1, the profile of the proton density distributions (3-parameter Fermi) would require luminosities of 10^{28} $cm^{-2}s^{-1}$. Then, to infer the neutron-skin density from the matter density, proton elastic scattering requires beam intensities of 10^6 particles per second. As a long term goal, such facilities would allow *(e,e'X)* inelastic scattering with selectivity to the transferred angular momentum, *(e,e'f)* electro-fission with detection of both fragments, and ultimately *(e,e'p)* quasi-free scattering studies with radioactive ions.

How do nucleon correlations appear in dilute neutron matter?

It is well known that correlations play a major role in the nucleus, although their precise origin and evolution with binding energy and isospin still remain to be explored.

Nuclear pairing is the most obvious manifestation where the spatial and momentum correlations between pairs of nucleons yields enhanced binding energy and tip the balance between a nucleus being bound or not, fissile or fissionable, with a corresponding imprint on the nuclear structure. The existence of different types of nucleon pairing, T=0 or T=1, and the spin-dependence of the nuclear force provides a rich spectrum of correlated structures with a sensitivity to the spin alignment of the nucleons with a fundamental link to the underlying exchange processes. It is speculated, but not yet proven, that a condensate of n-p T=0 pairs may develop in heavy self-conjugate nuclei close to ^{100}Sn.

At the neutron drip-line the effects of neutron-neutron correlations are manifest in the Borromean nature of ^{6}He, ^{8}He, ^{11}Li and ^{14}Be. The origin of di-neutron spatial correlations and their persistence in heavier nuclei remain challenging to observe. Similarly, on the proton-rich side ^{10}C may be thought of as four-fold-Borromean system composed of ^{4}He+^{4}He+p+p. In this particular instance the very high binding energy of the α particle is playing a driving role.

When the decay threshold of cluster, e.g. alpha, is reached, the nucleus has the opportunity to transform its internal energy into the binding energy of the cluster and the nuclear structure may reach a form, which asymptotically approximates a free cluster and core. Such nuclear states are embedded in the continuum, and as such coupling to the continuum is likely to have a significant influence in the appearance of the cluster states whose nature is imprinted in the continuum (see Figure 8). Cluster correlations are also an important feature in heavier nuclei. Recent generalised relativistic functional calculations predict a significant alpha cluster at the surface of heavy nuclei with a more pronounced effect in neutron-rich nuclei. A systematic search from alpha quasi-free scattering or transfer along isotopic chains should be pursued in the coming years. The surface alpha clustering affects the correlation of the neutron skin thickness of heavy nuclei with the density dependence of the symmetry energy.

Often the precision in quantities such as phase-shifts, electromagnetic transitions or in weak decays is not sufficient for testing new theories. This is particularly true for continuum properties either of excited states of bound nuclei or for systems beyond the drip-lines. A coordinated experimental programme to measure moments, transition strengths, (decay) widths, and determine the complete spectroscopy of nuclear systems is essential. In the particular case of electromagnetic decays from unbound states with branching of 10^{-2}-10^{-4} large gamma spectrometers are necessary. Selective reaction mechanisms, using both radioactive and high intensity stable beams, must be employed to enhance the formation and sensitivity to cluster structures in nuclei.

For the study of clusters, key nuclei might include ^{12}C (particularly the spectroscopy above the alpha-decay threshold, including the Hoyle-state), molecular nuclei such as ^{9}Be and ^{9}B (where it is believed that neutrons and protons may be exchanged between cluster cores), drip-line nuclei from the helium to oxygen isotopes, and alpha-particle states above decay thresholds.

When reaching the limits of existence the coupling between bound nuclear states and the continuum may also lead to new decay modes. At the proton drip line, one- and two-proton emissions have been discovered that enable the validity of nuclear models to be tested beyond the drip line. The dynamics of the emitted protons give insight into the pairing and the tunnelling in nuclear matter, provided the angular correlations between protons are precisely measured. Up to now, such studies have been done partially in ^{45}Fe and the new generation of high intensity secondary beams offers new opportunities. One difficulty with two-proton radioactivity lies in the fact that the correlations between the emitted protons are somehow washed out by the Coulomb interaction. In order to test theory it is very interesting to study two-neutron decays from ground states or from isomeric states close to the neutron drip line.

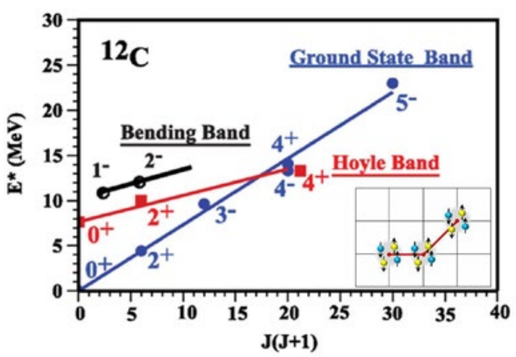


Figure 8. Spectroscopy of ^{12}C. Recent measurements of high excited 2^+ and 4^+ states associated with rotational states built on the Hoyle intrinsic state configuration are consistent with a three alpha structure, in agreement with state-of the-art *ab initio* lattice calculations (inset).

How does nuclear structure change with temperature?

Investigating properties of nuclear systems as a function of intrinsic excitation energy (temperature) is crucial for studying nuclear structure beyond a pure mean field description. From the ground state up to the particle separation energy, the weakening of pair correlations of protons and neutrons (Cooper pairs) boosts the level density exponentially. Around the neutron binding energy, an almost fully chaotic behaviour leaves a fingerprint on the nearest-neighbour spacings of neutron resonances. Neutron-resonance and capture data, from e.g. the n-ToF group at CERN, reveal very important information in this energy regime.

The γ-ray strength function (γSF), see Figure 9, together with the nuclear level density (NLD), are crucial for several fields of science and applications, being related to fundamental properties of the structures and dynamics of heated nuclear quantum systems. At low spins, the γ-decay channel plays a pivotal role in estimating reaction rates for the nucleosynthesis in extreme astrophysical environments. This concerns in particular (n, γ) reaction rates (see Figure 9), as well as our understanding of neutron capture in fusion processes for energy production, and for the design and modelling of next-generation nuclear power plants.

By moving towards more and more exotic systems, the continuum domain takes over at lower excitation energies due to a rapidly decreasing nucleonic threshold, and, for super-heavy nuclei, a lowering of the fission barrier. The γ-decay strengths will have a stronger coupling to the particle decay channel and to the occurrence of chaos that may spread the particle widths over

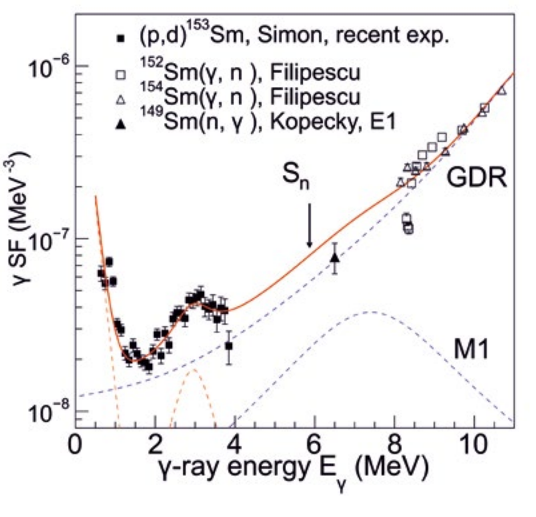


Figure 9. Low-lying γSF structures in Sm isotopes: the strength at < 1 MeV and the scissors resonance at 2-4 MeV, may change the (n,γ) reaction rates by 2-3 orders of magnitude for very neutron-rich Sm isotopes relevant to r-process nucleosynthesis.

many states. Fundamental questions concerning the quasi-continuum remain, such as the transition to chaos and the validity of the Brink-Axel hypothesis stating that the γSF only depends on the γ energy. Experimental and theoretical effort is required to attack these challenges in the next decade.

Finally, the temperature degree of freedom also offers the possibility of investigating the restoration of one of the most important symmetries in the atomic nucleus, namely isospin, which is broken - at the percent level - by the Coulomb interaction. At high temperature, isospin symmetry is partially restored, due to the short decay time of the compound system. This can be probed, in a unique way, by the γ-decay properties of the Giant Dipole Resonance in the hot compound nucleus. The isospin impurity at zero temperature can be also deduced, as recently shown in the heavy N=Z nucleus ^{80}Zr. Heavier systems, close to ^{100}Sn, will be within reach with intense beams which, combined with the use of powerful γ-ray detector arrays, offers a unique opportunity to elucidate changes in the system with intrinsic excitation energy, opening new venues in exotic nuclei.

REACTION DYNAMICS

Investigation of correlations by means of transfer and knockout reactions

The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighbouring states. These structure properties may influence in a significant way the evolution of the collision of two nuclei. Two-nucleon transfer constitutes the key probe in the study of pairing in nuclei, see Box 5.

The search of signatures of pairing has been mainly attempted via the measurement of two-particle transfer channels, in particular, via the extraction of enhancement coefficients, defined as the ratio of the cross section with predictions using uncorrelated states. This has motivated the re-examination of microscopic theories, which incorporate neutron-neutron correlations in the reaction mechanism. Extension of these microscopic theories to two-nucleon transfer processes involving both protons and neutrons is also needed.

From the experimental side, the decisive contribution came from the study of reactions in which a correlated pair of nucleons is added or removed from the nucleus as in the (t,p) or (p,t) reactions, for neutron transfers, or (^{3}He,p) for proton-neutron transfers, and also with high–energy knock-out reactions. More recently, pair correlations were probed in heavy ion collisions, where transfers of different nucleon pairs can be studied simultaneously. Such studies are especially relevant for future investigations with radioactive beams and it is important that new, high quality data are collected.

Modelling fusion

Nuclear fusion involves the collision of two quantum many-body systems that coalesce to form a "hot" fused nucleus following full dissipation of their relative kinetic energy. Experimentally, the challenge is to identify the processes that trigger dissipation as the two nuclei approach one another, determine their evolution with the collision energy, and quantify their influence on fusion. Theoretically, the challenge lies in how to incorporate dissipation into models that retain the essential quantum many-body nature of the colliding nuclei.

For light weakly-bound nuclei (e.g. ^{6,7}Li, ^{9}Be) recent experimental results have corroborated the suppression of the above-barrier fusion cross sections (25-40%) relative to single-channel or simple coupled-channels predictions. Although the effect has been attributed to the coupling to two-body breakup channels into ^{2}H, ^{3}H and ^{4}He clusters, recent exclusive breakup measurements indicate that the reactions causing breakup are more diverse than commonly assumed. These works postulate transfer-induced breakup as a significant contributor of fusion suppression.

At sub-barrier energies, the situation seems to be less clear and continues to be a matter of debate (Figure 10). Just below the barrier, data show an enhancement of the fusion cross section with respect to single-channel prediction. However, at deep sub-barrier energies, a hindrance with respect to the coupled-channels prediction has been reported and several interpretations provided, from a possible inner pocket in the ion-ion potential, to a transition from a two-body regime to a one-body regime.

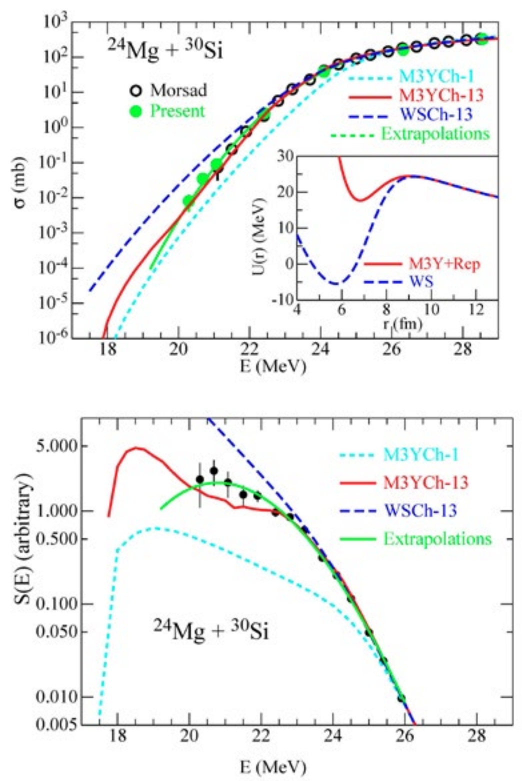


Figure 10. The phenomenon of heavy-ion fusion hindrance at deep sub-barrier energies. The excitation function (top) and the astrophysical S-factor (bottom), together with coupled-channels calculations performed with different potentials (see inset) and different number of channels. Thanks to the development of detection systems it has been possible to extend fusion excitation functions to low energies. The suppression of the fusion probability at these low energies was explained in terms of the saturation properties of nuclear matter (the inclusion of a repulsive core in the nuclear potential). Therefore such studies have a direct impact on the description of the astrophysical processes by providing more reliable recipes for extrapolation of the relevant cross sections and reaction rates into the temperature range of interest.

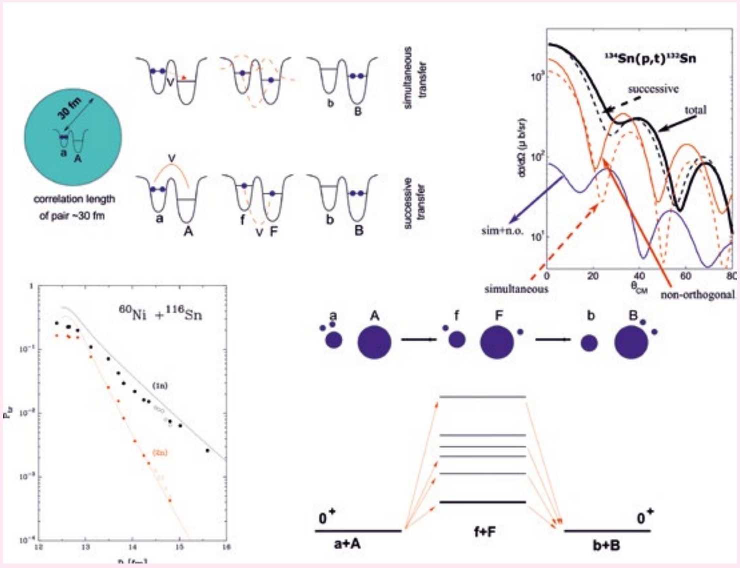
The behaviour of the heavy-ion fusion cross sections at extreme low energies has a direct impact on the description of the astrophysical process. In many cases, the cross-section measurements in the critical energy windows are still unattainable in the laboratory, and thus extrapolations to lower energies must be used in simulations, which will be strongly influenced by the fusion hindrance.

Heavy-ion induced fusion is so far the sole process giving access to the superheavy elements. The heaviest known elements up to oganesson (Og, Z=118) are accessible in reactions of ^{48}Ca (Z = 20) with actinide targets. Progressing to yet heavier elements requires the use of heavier projectiles due to the lack of target elements beyond californium (Cf, Z = 98) in sufficiently large quantities. The experimental systematics acquired over the past 15 years or so for ^{48}Ca-induced reactions is thus of limited applicability for the selection of the optimum nuclear reaction and projectile beam energy to search for elements 119 and beyond. In this situation, nuclear reaction theory is urgently needed to guide experimental efforts to provide the optimum reactions and beam energies and give good cross-section estimates for the search for new elements.

Interfacing structure with reaction observables

The extraction of physically meaningful information from reaction observables requires, in addition to an adequate modelling of the reaction dynamics, the use of realistic structure models and a proper understanding on how the structure information can be single-out from the reaction dynamics. It has become clear that the structure models used for a number of reaction calculations are often too simplistic.

In the light region of the nuclear chart, it has become apparent that the strict few-body picture, which proved to be very useful to understand the structure and reactions of weakly-bound nuclei, is sometimes inadequate and core excitations/polarisations are indeed needed for a correct description of the data. Along the same lines, recent studies on one- and two-nucleon knockout reactions have shown that the inclusion of microscopic overlaps obtained from



Box 5. Two particle transfer reactions as a tool to study pairing correlations.

The comparison of experimental absolute cross sections with a suitable microscopic reaction theory provides insights on nucleon-nucleon correlations. Modern implementations of two-nucleon transfer formalisms have proven to be able to account for the absolute neutron pair transfer cross sections within their experimental errors. State-of the art examples are given for ^{132}Sn+p (top-right panel) and for ^{60}Ni+^{116}Sn (bottom-left panel). The scenario of the simultaneous and sequential mechanisms of the transfer of two nucleons is schematically presented in top-left panels, where inside of the pair correlation length (blue shaded area) the interaction (mean field) potentials and the non-zero overlap of the wave functions are drawn.

Many reaction paths arising from the simultaneous and sequential mechanisms have to be included, as displayed on bottom-right panel with the schematic representation of the two-neutron transfer, from the incoming to outgoing channels, through intermediate channels. The sequential contribution turns out to be dominant. Indeed, the large correlation length of the nucleon Cooper pair, ensures that pairing correlations are maintained during the transfer process, also in the case of sequential transfer.

It will be important to investigate how and to what extent these structure properties influence the evolution of the collision of two nuclei, keeping in mind the importance of the connection between reaction and structure aspects. Such studies are particularly relevant for nuclei far from the stability valley where correlations may play an important role in stabilising the system by increasing their binding energy.

ab-initio calculations, including 3-body forces, provides improved results as compared with the conventional shell-model inputs.

Accessing structures beyond the proton/neutron driplines

Many different types of nuclear reactions produce nuclei far from stability and thus reaction theory can help to extract useful information (e.g. resonances, virtual states, E1 strengths, etc.).

The recent revival of transfer reaction studies benefited from the construction of the new generation of detector arrays (PRISMA, VAMOS, EXOGAM and AGATA). One of the promising tools for the production of the neutron-rich heavy nuclei is the use of the multinucleon transfer reactions at energies close to the Coulomb barrier. These nuclei, which are relevant for the r-process, play a critical role for predictions of the synthesis of the heaviest elements.

The experimental data should be understood within dynamical models (semiclassical as well as quantum) of heavy-ion collisions. Since all the reaction channels (quasi-elastic and deep inelastic scattering, quasi fission, fusion-fission) are substantially coupled and overlap with each other, a model should consider the evolution of the nuclear system from the configuration of two well-separated nuclei approaching each other in the entrance channel and up to formation of final fragments. One of the key but still unanswered questions here is the role of the shell effects influencing the dynamics of nucleus-nucleus collisions.

By using heavy-ion fusion reactions the study of the nuclear structure has been extended to regions of very high angular momentum and large excitation energies. In the heavy-ion transfer reactions close to the Coulomb barrier, the transfer process maximises the transferred angular momentum to allow a good matching

Box 6. Toward a consistent determination of spectroscopic strengths

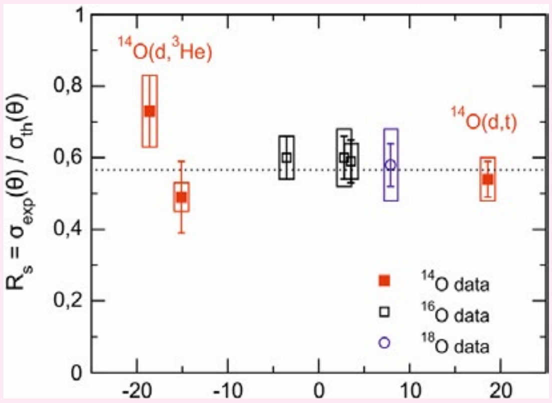
Correlation effects play a key role in the structure of nuclei. Correlations give rise to fractional occupation of single-particle orbits and a spread of the single-particle strengths over a wide range of excitation energies. Although not strictly observables, single-particle strengths are conveniently quantified in terms of spectroscopic factors (SF).

Under suitable conditions, reaction experiments, involving the removal or addition of nucleons, can be used for extracting SF. Examples of these are nucleon knockout, transfer and electron (e,e'p) reactions. To isolate the structure content, a proper understanding and modelling of the reaction mechanism is mandatory.

Studies of one-nucleon knockout, transfer and (e,e'p) reactions have shown that the extracted SF are systematically smaller than those predicted by truncated-space shell-models calculations. This reduction of the SF strength has been ascribed to the presence of additional correlations not included in these structure models.

An intriguing additional reduction has been reported in the case of knockout of deeply-bound neutrons, in proton-rich nuclei, or deeply-bound protons, in neutron-rich nuclei. More specifically, the ratio between the experimental and theoretical cross sections (Rs) decreases monotonically as a function of the difference in separation energies |Sp-Sn|, becoming smaller as the separation energy of the removed nucleon becomes larger. This behaviour has been attributed to a reduction of the occupancy for deeply bound orbits due to additional correlations, linked to the large asymmetry in the proton and neutron Fermi energies. However, recent transfer experiments, involving in some cases the same nuclei, do not seem show this suppression.

Since reliability of the extracted SF require that they do not depend on the specific process used for their extraction, the situation calls for a re-examination of the models used to in the analysis of these reactions (for example, the eikonal approximation standardly assumed in the analysis of knockout reactions) and the investigation of possible mechanisms which might affect their interpretation, such as multiple scattering, core excitations and nucleon evaporation.



Recently, proton-knockout experiments of the form (p,pN) have been put forward as a promising alternative to heavy-ion knockout reactions, since they are expected to probe deeper parts of the wave-function of the removed nucleon. Reaction models to describe these processes, such as DWIA, while used extensively in the 1970s-80s with stable nuclei, are now being re-examined and upgraded by several groups.

between the orbital angular momentum of the involved states, and this leads to the strong population of the yrast states in the final nuclei. On the other side, the excitation and transfer processes are mediated by the well-known single-particle form factors for the fermion degrees of freedom and by the collective form factors for the vibrational or rotational modes. This makes such reactions suitable for studies of the important couplings (fermion-fermion, fermion-boson).

Accessing extreme deformations and rare fission modes

Photofission measurements with high-brilliance quasi-monochromatic gamma beams at ELI-NP will open the possibility for highly selective investigation of extremely deformed nuclear states in light actinides and can be used to better understand the landscape of the multiple-humped potential energy surface in these nuclei. While the appearance of a deep superdeformed minimum in the potential energy surface has been observed and described a long time ago, the existence of a third extremely deformed hyperdeformed minimum is a long-standing problem in nuclear physics that still awaits solution.

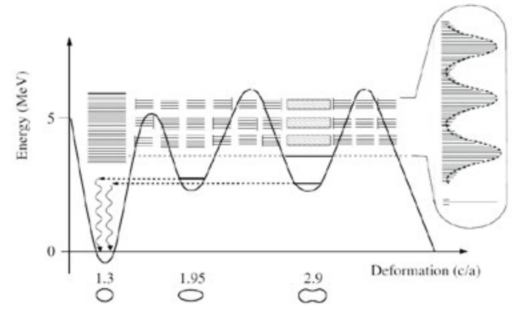


Figure 11. Schematic description of the occurrence of transmission resonances in prompt fission through a triple humped fission barrier.

One experimental approach to investigate extremely deformed collective and single-particle nuclear states in light actinides is based on the observation of transmission resonances in the prompt fission cross section (Figure 11). By observing transmission resonances caused by resonant tunnelling through excited states in the third minimum of the potential barrier as a function of the energy allows us to identify the excitation energies of the hyper deformed states.

The capabilities of the gamma beams in terms of high spectral density and narrow bandwidth of ELI-NP will allow for the identification of sub-barrier transmission resonances in the fission decay channel with integrated cross- sections down to $\Gamma\sigma$ ~ 0.1 eV·b, where Γ is the resonance width.

High intensity quasi-monochromatic gamma-ray beams at ELI-NP will be used for the first time to search for rare fission modes such as true ternary fission. Nuclear fission accompanied by light charge particle emission will be studied. As ternary particles are released close to the scission point they provide valuable information about the scission point and fission dynamics. The use of linearly polarised gamma-ray beams has the advantage of fixing the geometry of the fission process thus facilitating a detailed study. These studies aim at revealing the mechanism of ternary particle emission and its connection to the deformation energy, spectroscopic factors or formation of heavier clusters.

THE NUCLEAR EQUATION OF STATE

The Equation of State (EoS) of infinite nuclear matter describes the relation, E(T,ρ), between the energy per nucleon, E, temperature, T, and nucleon density ρ. The EoS plays a key role in reaction mechanisms and in collective excitations of nuclear systems. Nuclear systems are generally composed of two distinct fermions, neutrons (n) and protons (p). Hence, the isospin asymmetry $\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$ is also crucial in determining the properties of nuclear matter. Distinct phenomena are predicted to occur whether symmetric (δ=0) or asymmetric (δ≠0) nuclear systems are investigated. The top panel on Figure 12 shows a schematic view of the phase diagram of nuclear matter on the temperature-isoscalar density ($\rho=\rho_n+\rho_p$) plane. The occurrence of phase transitions for systems in the spinodal instability region has been the focus of several investigations both experimentally, with heavy-ion collision studies, and theoretically by means of transport model calculations. The less explored EoS for asymmetric nuclear matter, E(ρ,δ) with δ≠0, is described as the sum of a symmetric term (δ=0) and an isospin asymmetry term: $E(\rho,\delta)=E(\rho,\delta=0)+S(\rho)\times\delta^2$. The relevant effects of the so-called symmetry energy, S(ρ), with its density dependence around and away from saturation density $\rho_0=0.16$ fm^{-3}, represent the main goal of present heavy-ion collision studies at several laboratories. The bottom panel of Figure 12 displays different theoretical predictions of the density dependence of the symmetry energy. Heavy-ion collisions at intermediate energies have provided some range of constraints on S(ρ), as indicated by the shaded green area on the figure. Since uncertainties still exist, extensive studies are performed around saturation densities, $\rho\approx\rho_0$, as well as at sub-saturation ($\rho<\rho_0$) and supra-saturation ($\rho>\rho_0$) densities.

As in ordinary matter, collective properties such as phase transitions and collective vibrations around saturation density, are directly linked to the effective interaction acting between its components. Moreover, nuclear forces and nucleon-nucleon correlations induce clustering phenomena in matter at low densities, $\rho<1/10\rho_0$, playing an important role in core collapse supernovae and neutron stars. Such a dilute state of nuclear matter can be accessed in heavy-ion collisions. Nuclear physicists and astrophysicists are engaged in investigating the EoS.

It has been found that few-body fits have not sufficiently constrained three-nucleon force contributions around nuclear saturation.

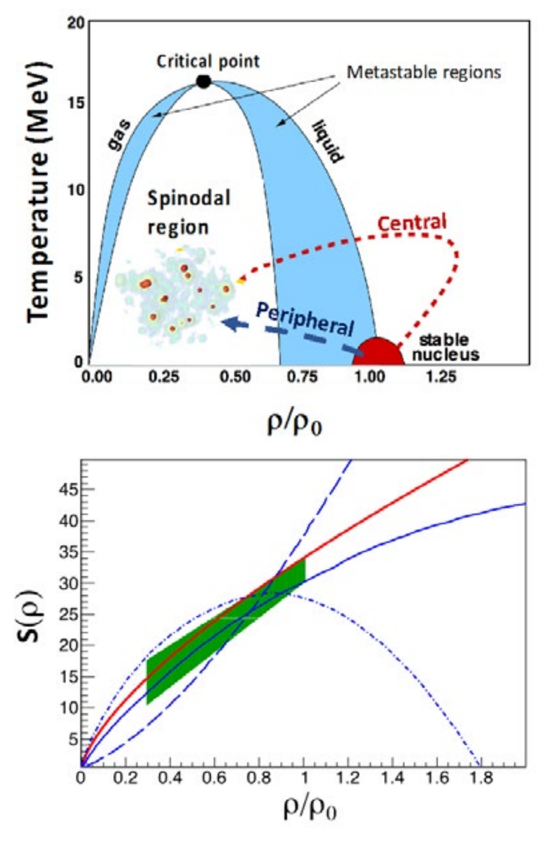


Figure 12. Top: Spinodal instability region of the nuclear EoS on the temperature-density plane. Dashed lines indicate paths followed by systems produced in heavy-ion collisions. Bottom: Schematic density dependence of the symmetry energy which could be predicted by theoretical calculations (lines) and present status of constraints provided by heavy-ion collision measurements.

The accurate reproduction of binding energies and radii of finite nuclei simultaneously with the main properties of nuclear matter saturation point therefore remains one of the main challenges in ab initio calculations. Various solutions to this problem have been proposed, ranging from short-range correlations and Pauli blocking effects to the inclusion of many-body forces and the in-medium optimisation of nuclear forces.

The density dependence of the equation of state (EoS): incompressibility and symmetry energy

The EoS is governed by the incompressibility of nuclear matter, and the density dependence of the symmetry energy, S(ρ). Both quantities can be extracted or extrapolated from experimental data on heavy-ion collisions and collective nuclear excitations, both in stable and exotic systems. The incompressibility of nuclear matter is defined as the curvature of energy per particle at the saturation density ρ^0. In the case of heavy-ion collisions, measurements of in-plane and out-of-plane collective flow of protons, neutrons, clusters and kaons in Au+Au collisions at 100 MeV<E/A<10 GeV, when compared with transport model simulations, have led to incompressibilities K_∞ = 210-300 MeV. However, more extensive and precise investigations on K_∞ are performed using collective oscillation of nuclei around saturation density, namely the Isoscalar Giant Monopole Resonance (ISGMR) and the Isoscalar Giant Dipole Resonance (ISGDR). The value of K_0=240±30 MeV, obtained from experiments of alpha scattering at zero degree on ^{90}Zr, ^{144}Sm and ^{208}Pb, appears to be consistent with that from heavy-ion collision. However, such incompressibility values would lead to an overestimated value of the centroid energies of giant resonances in Sn and Cd isotopes. It is important in the future to resolve such discrepancies and improve our understanding of nuclear compressibility by studying isotopes of the same element extending into the unstable region of the nuclear chart. Scattering of alpha particle in inverse kinematics with radioactive beams will require the use of either active targets and/or of storage rings. The first measurements of this type were successfully performed and pave the way for interesting measurements in the future.

The density dependence of the Symmetry Energy

The density dependence of the symmetry energy, S(ρ), needs to be explored with beams of nuclei over a wide range of N/Z (and thus δ) asymmetries. Nuclear structure and dynamics probes are sensitive to the strength $S_0=S(\rho_0)$, and the slope, $L \propto dE/d\rho|_{\rho_0}$, around saturation density, $\rho=\rho_0$. These quantities govern ground state and excited state properties of nuclei, collective excitations, such as the Pygmy Dipole Resonance (PDR, Box 5), and neutron/proton transport phenomena in heavy-ion collisions. The S_0 and L parameters also govern the dominant baryonic contribution to the pressure in neutron stars affecting their inner crust and radii. Thus investigations on nuclear properties as well as astrophysical observations and calculations need to provide consistent constraints on S(ρ). Results providing interval values for S_0 and L values, as obtained by different techniques, are displayed in Figure 13. Regardless of the moderate agreement between different results, it will be important to achieve consistent descriptions of the density dependence of the symmetry energy from laboratory measurements as well as astrophysical observations, possibly reducing uncertainties originating from both experimental accuracy and model dependencies.

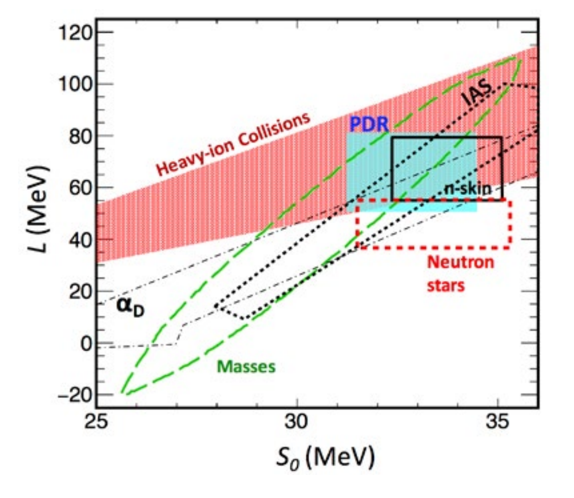


Figure 13. Ranges of strength, S_0, and slope, L, of the symmetry energy at saturation density, determined from different investigations in nuclear physics and astrophysics.

Investigations around saturation densities

The symmetry energy at saturation density is well known in the liquid-drop model and it affects significantly the binding energy of nuclei, the neutron skin thickness (i.e. the difference of the neutron and proton rms radii in heavy neutron rich nuclei), and excited state properties such as the energies of isobaric analogue states (IAS) and collective excitations. Experimental measurements explore a range of observables that are sensitivity to the symmetry energy. Among them can be mentioned: measurements of the difference of binding energy per nucleon, B/A, between even-even isotope pairs of different elements and the Lead-Radius Experiment (PREX) at the Jefferson Laboratory to determine the of ^{208}Pb to about 1% accuracy by means of parity-violating electroweak asymmetry in the elastic scattering of polarised electrons from ^{208}Pb targets; proton elastic scattering, on ^{58}Ni and ^{204,206,208}Pb isotopes; measurements of the energy of isobaric analogue states (IAS) in a number of nuclei. Some results obtained from these measurements range in the different areas indicated on Figure 13.

The Giant Dipole Resonance (GDR), is a clear probe of the symmetry energy around saturation density. In particular, the nuclear polarisability αD (defined as the $1/\omega^2$-weighted integral of the photo-absorption cross section) and the strength of the Pygmy Dipole Resonance are connected with the symmetry term of the nuclear EOS. The "slope" parameter L can be deduced due to its links to the energy-weighted sum rule (EWSR) exhausted by the PDRs and to the neutron-skin thickness.

A precise measurement of the nuclear polarizability requires detailed studies of the photo-absorption cross section, representing a challenging task in exotic systems. The dipole polarisability in ^{68}Ni, has been recently extracted at GSI using Coulomb excitation in inverse kinematics at the R3B-LAND setup.

This experiment paves the way to future investigations in neutron rich systems along isotopic chains.

Investigations away from saturation densities: heavy-ion collisions

Heavy-ion collisions between N/Z-asymmetric nuclei represent the only terrestrial means to explore the equation of state and the symmetry energy away from saturation densities. The intermediate energy regime (E/A=20-100 MeV) explores nuclear matter at sub-saturation density ($\rho<\rho_0$), while relativistic beam energies (100 MeV<E/A<1 GeV) allow supra-saturation densities to be probed (up to $\rho\approx 2\rho_0$). The hot and compressed systems evolve with time under the effect of nuclear and Coulomb forces. Microscopic transport models provide simulations of such evolution, with specific density functionals of the symmetry energy, $S(\rho)\propto(\rho/\rho_0)^\gamma$, that are plugged-in as input parameters. The γ parameter then defines the stiffness of such density dependence.

Sub-saturation densities

The dashed lines in Figure 12 schematically show the paths followed by a finite nuclear system produced in a collision at intermediate energies. The red and blue colours refer to central and peripheral collisions, respectively. In the first case, the system undergoes a strong compression stage accompanied by an increase of temperature. Then nuclear matter may expand towards the spinodal instability region at sub-saturation densities, $\rho<1/3\rho_0$, and finite temperatures where a liquid-gas phase coexistence may occur.

Such collisions were extensively studied with INDRA (GANIL) and CHIMERA (INFN-LNS), respectively. The results obtained from studying multifragmentation phenomena, collective flow, fragment emission time-scales, fluctuations analyses, bimodality and calorimetric measurements have increased our understanding of phase transitions and the EoS. The availability of beams over a wide range of N/Z asymmetries allows investigation of the effect of isospin asymmetry on phase transitions. In particular, "isospin distillation" has been observed: due to the symmetry potential pushing neutrons towards low density regions, the gas phase is expected to be more neutron-rich (Ngas>>Zgas) than the liquid phase (Nliq≈Zliq). Such a phenomenon has been studied by measuring light fragment (Z=3-7) production in ^{112,124}Sn+^{58,64}Ni collisions (CHIMERA LNS). Better constraints will be obtained in the future using the FAZIA array, equipped with digital pulse-shape, allowing to extend high isotopic resolution to Z>20.

Important probes of the symmetry energy arise also from the pre-equilibrium emission of neutrons and protons. Therefore neutron detection is required.

In peripheral collisions the quasi-projectile (QP) and quasi-target (QT) partners exchange nucleons through a low-density neck region. During this process two mechanisms are at play, namely isospin drift and isospin diffusion, which depend on the symmetry energy. Isospin drift consists of a net migration of neutrons towards the low-density neck region and is governed by the slope L of the density dependence of the symmetry energy at $\rho=\rho_0$. A study of isospin drift in ^{124}Sn+^{64}Ni at E/A=35 MeV was made (CHIMERA LNS) and there the average N/Z of neck fragments over a wide range of charges Z (Figure 14) was compared with Stochastic Mean Field (SMF) calculations leading to L≈80 MeV. Isospin diffusion occurs when the colliding projectile and target nuclei have different N/Z asymmetries, as in ^{124}Sn+^{112}Sn collisions. In this case, the strength S_0 of the symmetry energy at $\rho=\rho_0$ mostly affects such mechanism together with the interaction time. Isospin diffusion has been investigated with INDRA (GANIL). Such studies may be affected by discrepancies arising from different transport model approaches (mean-field models, molecular dynamics models, etc.). Therefore efforts to achieve a consistent description of symmetry energy effects in different models are needed.

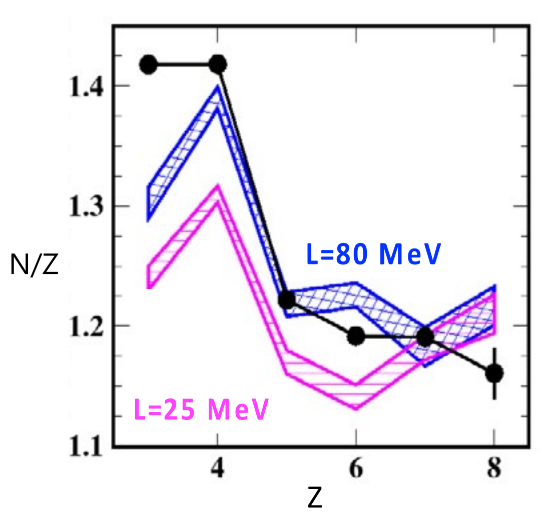


Figure 14. Data points: Average isospin asymmetry N/Z versus charge Z of fragments emitted dynamically from the neck region in ^{124}Sn+^{64}Ni at E/A=35 MeV. Coloured bands: results of Stochastic Mean Field simulations with different density dependences of the symmetry energy (corresponding to L=25 and 80 MeV).

An interesting aspect of heavy ion reactions, observed in an experiment with VAMOS-INDRA (GANIL), is the possible production of boson condensation in hot nuclei. Light particle emission allows densities and temperatures of the decaying hot nucleus at different excitation energies to be deduced (Figure 15). Densities extracted from bosons (deuterons and alphas) result to be higher than those extracted from Fermions (protons). Further investigations searching for signals of Boson Condensation and Fermi Quenching in the decay of hot nuclei seem to be promising.

Interplay of EoS and structure properties

The interplay between reaction mechanisms and structure properties manifests itself with phenomena such as alpha clustering, predicted to affect the low density behaviour of the nuclear EoS. Clustering plays a key role even at low energies, E/A=8-16 MeV, where an interplay between fast pre-equilibrium and equilibrated thermal emissions exists. Reactions ^{16}O + ^{65}Cu at E=265 MeV and ^{19}F + ^{62}Ni at E=304 MeV, induced by projectiles with (^{16}O) and without (^{19}F) alpha-clustering structure, were studied with GARFIELD (INFN-LNL). The different alpha structure properties of projectile nuclei are reflected on the measured shape of their energy spectra. Such phenomena may be important near the drip–lines, and will be better investigated in the future at the SPES, HIE-ISOLDE and SPIRAL2 facilities.

Supra-saturation densities

At beam energies E/A>200 MeV heavy-ion collisions produce systems at densities as high as $\rho\approx2\rho_0$. The elliptic flow of nucleons and the meson (pions and kaons) production carry information about the density dependence symmetry energy S(ρ). Measurements of the elliptic flow of protons and neutrons in Au+Au collisions at E/A=400 MeV were made with LAND-CHIMERA-KRATTA experiment at GSI and provided L≈72±13 MeV.

At energies E/A>300 MeV/nucleon, the relative yields of positive and negative pions, π^+/π^-, as a function of their kinetic energies is also expected to provide information for S(ρ). Measurements of π^+/π^- ratios with FOPI (GSI) led to conflicting conclusions and this seems to be related to the difficulties in producing realistic transport model predictions including the treatment of pion production, absorption and re-scattering in the

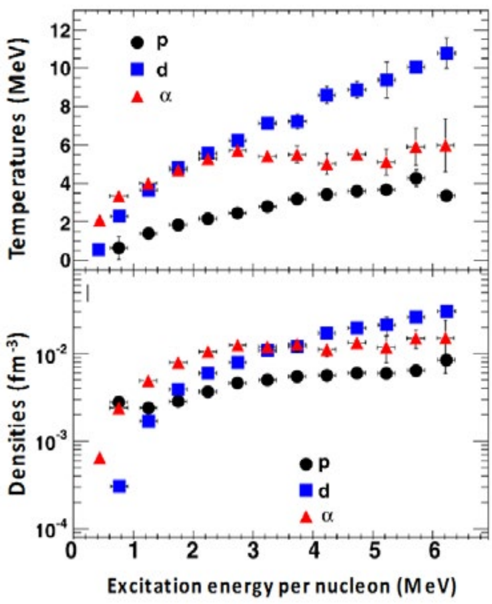


Figure 15.Temperatures and partial densities probed by different particle species (protons, deuterons and alphas) as a function of excitation energies of quasi-projectile decay in peripheral $^{40}Ca+^{40}Ca$ collisions at E/A=35 MeV.

nuclear medium. In contrast to pions, kaons are mainly produced at high densities during the early stage of the collision and are essentially free of subsequent reabsorption effects, and thus promising to provide more probes of the symmetry energy.

Open issues and perspectives

Extraction of meaningful structure information from reaction studies requires a proper understanding and modelling of the reaction dynamics. This includes a better understanding on the interplay and relative importance of different degrees of freedom taking place in the reaction, namely, collective excitations, rearrangement channels and breakup. In particular, these studies should improve our comprehension of the nuclei in the so-called island of inversion, where *weak-binding* and *deformation* coexist.

It would be desirable to clarify the connection between the reaction dynamics and the structure information that can be actually accessed from these experimental observables.

Time Dependent Hartree-Fock calculations, whose feasibility has benefited from the use of modern HPC, need to be systematically applied to various phenomena: transfer, deep-inelastic, fission, fusion. The incorporation of correlations beyond mean field would be a natural and advisable step forward in these studies.

Due to its potential implications, it is advisable to investigate the possibility of extracting information on the neutrinoless double-beta decay matrix elements by means of double-charge exchange reactions. Since, at present, no exact microscopic reaction theory exists for these reactions, for example they treat exchange terms approximately, an upgrade of existing formalisms is required.

Experimentally to face future challenges in nuclear structure and dynamics cutting-edge facilities and instrumentation are essential.

For nuclei far from stability NuSTAR of FAIR (with all its instrumentation) and HIE-ISOLDE, SPES and SPIRAL2 (the latter three linked together with the EURISOL Distributed Facility) are necessary to advance in the understanding of interactions in nuclei, of the different nuclear degrees of freedom, and of reactions.

The completion and operation of the ELI-NP facility will provide important capabilities and opportunities for the exploration of new frontiers in nuclear photonics.

The availability storage rings at HIE-ISOLDE and the HESR of FAIR will provide unique physics opportunities in Europe.

The AGATA array is a unique and world-leading device for high-resolution gamma-ray spectroscopy for nuclear structure studies. Timely completion of the AGATA gamma-ray spectrometer is strongly needed.

Small and medium scale accelerator facilities in Europe play and will continue to play a crucial role in the joint effort of understanding nuclear structure.

FACILITIES AND INSTRUMENTATION

Radioactive beam facilities

During the past 30 years, the first generation of radioactive beam (RIB) facilities based on the complementary methods of, in flight separation (GANIL and GSI) and the ISOL approach (ISOLDE and SPIRAL1) have enabled tremendous progress in the study of exotic nuclei to be made and stimulated the efforts to build new radioactive ion beam facilities. Europe has led the way in radioactive beam development. Both in-flight separation and the ISOL approach, combined with different post-processing of the radioactive nuclei, will form the pillars of the RIB facility network in Europe.

FAIR will be the European flagship facility for the coming decades. The unique accelerator and experimental facilities will allow for a large variety of unprecedented fore-front research in physics and applied science. The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale, deepening our understanding of fundamental questions. Prior to the commencement of the modular start version of FAIR, the upgraded GSI facility will continue to perform a science programme and instrumentation commissioning in a phase 0 of FAIR. The urgent completion of FAIR, the Super-FRS and NUSTAR, are of utmost importance for the community. In the interim period, it is vital that a high-level research programme and use of the new detectors for FAIR at GSI continues using the existing beams and facilities.

The ultimate ISOL facility in Europe will be EURISOL for which an extensive R&D programme and a design study has been carried out proposing that it will consist of a high energy and power superconducting linear accelerator. Prior to EURISOL the EURISOL DF project aims at integrating the ongoing efforts and developments at the major ISOL facilities of HIE-ISOLDE, SPES and SPIRAL2, the planned ISOL@MYRRHA facility, and the existing JYFL and ALTO and COPIN facilities. EURISOL DF will use the synergies and complementarities between the various facilities to build a programme of research to bridge the gap between present facilities and EURISOL.

An IGISOL facility for production of exotic neutron-rich nuclei using brilliant gamma-ray beams is being designed at ELI-NP. The energy distribution of the gamma-ray beams can be tuned such to optimally cover the energy region of the giant dipole resonance of fissile target nuclei making it an ideal tool to induce their photofission. The IGISOL technique allows for the extraction of the isotopes of refractory elements, which do not come out from standard ISOL targets.

Stable ion beam facilities and other techniques

High quality beams at moderate intensities (10^6-10^8 pps) and over a wide range of energies (ranging from few MeV's up to few GeV's per nucleon) are presently available at several European laboratories, playing a key role in structure studies (with particle and γ spectroscopy) and in nuclear dynamics to explore the isospin dependence of the nuclear equation of state. Very intense stable ion beams (SIB) are used to study superheavy element (SHE), rare phenomena relevant for nuclear astrophysics, nuclear structure at low, medium and high spin, exotic shapes, decay modes, clustering and collective motion in nuclear systems, nuclear ground state properties (masses, charges and moments) and near barrier transfer and fusion reactions. These challenges were championed in the ECOS report that recommended full support of such facilities to address challenges in searching for the limits of nuclear existence towards the n- and p-drip lines, as well as towards the regime of SHE, with beams at intensities as high as 10^{12}-10^{13} pps. The present and future SIB facilities include, the LINAG at GANIL, the UNILAC and future cw-linac at GSI, the ALTO facility at IPN Orsay, the accelerators at JYFL-Jyväskylä, KVI-CART-Groningen, LNL-Legnaro, LNS-Catania, NLC (Krakow-Warsaw) and the SHE factory at Dubna. The NUMEN project at INFN-LNS will lead to an increase of the superconducting cyclotron power from 100 W to 10 kW, that will allow the study of double charge- exchange reactions and measure matrix elements needed to study the double beta decay in neutrino related researches.

Intense neutron beams provide a unique opportunity for studies of neutron induced reactions and for applications. The ILL reactor in Grenoble is the world brightest continuous neutron source, feeding about 40 state-of-the art instruments. This includes the high-resolution spectrometer GAMS, the fission fragment recoil separator LOHENGRIN, and the multi-detector setup FIPPS, at which a rich γ-spectroscopy programme is foreseen, following neutron induced fission and neutron capture reactions on a large variety of targets. At CERN, the n-TOF facility produces neutrons by a pulsed beam of protons on a Pb spallation target. An intense wide neutron spectrum is created, with energies from a few MeV to several GeV. The workhorse of the facility is the Total Absorption Calorimeter, a 4π segmented array made of 42 BaF_2 scintillators. At LICORNE, IPN-Orsay, monoenergetic, kinematically focused, neutron beams with energies 0.5-4 MeV are produced by bombarding hydrogen-rich targets with intense ^{7}Li beams. Experimental campaigns make use of a modular setup based on Ge detectors coupled to large volume scintillators and detectors for fission products. In GANIL, the Neutron For Science facility will soon provide intense 1-40 MeV pulsed neutron beams produced from protons and deuterons accelerated by the LINAG on a converter.

Other accelerator-based probes are also important for nuclear physics research in Europe. The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) project is one of the three pillars of the pan-European ELI project aiming at the use of extreme electromagnetic fields for nuclear physics research. The characteristics of the photon will allow new sensitivity to be reached, that is needed to approach a virgin science field at the frontier between the strong field QED and nuclear physics. Laser-driven nuclear physics will explore the possibilities of ion acceleration with solid state density bunches, giving the opportunities of producing very neutron-rich nuclei in fission-fusion reactions or studying nuclear reaction rates and isomer production in laser plasma. Applications of photon beams in nuclear energy, medicine, space science, industrial radioscopy and tomography are also planned.

Europe has many small and medium scale facilities that are mostly associated with and/or run by universities. The presence of unique instrumentation and the availability of a large variety of stable beams at these facilities, combined with easy access, offers the possibility of forefront research in specific areas of fundamental and applied nuclear physics. They are also important for the training and education of the next-generation researchers as well for the development and testing of new instruments and techniques.

Instrumentation

Separators, spectrometers and associated detection for nuclei identification

The production of exotic nuclei is closely linked to the availability of separators and spectrometers in order to select and identify the nuclei or reactions of interest.

One method that is used is high-energy radioactive ion production in which the primary heavy-ions impinge on a light and thin target. The projectile or fission fragments can be separated in-flight within some hundreds of nanoseconds. In-flight separation offers the possibility to have momentum resolving powers of up to 20,000 and provides isotopically pure or cocktail beams and fully-stripped ions up to uranium. The Super-FRS at FAIR will be the most powerful in-flight separator for exotic nuclei up to relativistic energies (~1GeV/nucleon). A novel development is high-resolution spectroscopy of hypernuclei, exotic atoms and nucleon resonance studies in exotic nuclei using hadron spectrometers at the central focal plane of the separator.

Recently, in collisions at energies near the Coulomb barrier, the isotopic identification of fission fragments has been achieved using VAMOS++ at GANIL, and identification of both transfer binary fragments using PRISMA and kinematic coincidence arm at LNL. The use of the inverse kinematics makes it possible to exploit the unique performances of these spectrometers in terms of resolution and efficiency. A good isotopic separation enables the importance of secondary processes (like fission and evaporation), which may significantly modify the production yields in the heavy mass region, to be investigated. These findings will be exploited for nuclear structure studies of neutron-rich nuclei by means of prompt-delayed γ-ray spectroscopy. In addition, exploitation of the gas-filled separator RITU at JYFL continues to provide new insights into the structure of neutron-deficient and heavy nuclei. The programme at JYFL will be extended to lighter proton-drip line nuclei with the advent of the MARA mass spectrometer.

Fusion-evaporation reactions are mainly used to produce neutron-deficient nuclei toward the proton drip line and SHE and are used with efficient velocity filters (such as SHIP) or gas filled separators (such as TASCA, RITU). The challenge is to develop new separators able to handle very high intensities such as S3 installed in the experimental areas of the superconducting LINAC of SPIRAL2. It is designed for in-flight transmission and purification of rare reaction products combining a momentum selection plus a mass selection.

Within the ISOL approach, intense beams of exotic nuclei are extracted from ion sources at low energy (30-60 keV) although they are accompanied by a strong contamination of nuclei closer to the stability. Purification techniques are then mainly based on isobar separators. The actual challenge is to reach resolving power in the range of 20,000 (DESIR-HRS@SPIRAL2). Alternatively, a selection based on the chemical element (laser ionisation) can be done but this is not available for all elements. Another technique based on the use of devices like new Penning traps or multi-reflection time-of-flight mass separators are currently under development to increase the resolving power by one or two orders of magnitude. Isomer separation has been demonstrated at GSI using an MR-TOF-MS opening the possibility to produce pure isomeric beams. A new and important approach concerns the hybrid systems like the FRS Ion-Catcher combining gas cells with in-flight separators providing ISOL-type beams of short lived nuclei.

Detectors for structure and dynamic studies

Gamma-ray Detectors

The workhorses for high resolution gamma-ray spectroscopy are arrays based on Ge detectors, which have now reached the frontier of efficiency and sensitivity with AGATA, which will be the first 4π gamma-ray spectrometer solely built from Ge detectors. Being fully instrumented with digital electronics it exploits the novel technique of gamma-ray tracking. AGATA has been successfully operated since 2009 at LNL, GSI and GANIL, taking advantage of different beams and powerful ancillary detector systems.

AGATA has been successfully coupled to charged particles detectors (DANTE, LYCCA), high energy γ-ray scintillators (HECTOR, HELENA), magnetic spectrometers (PRISMA, VAMOS++) and the fragment separator (FRS). In the future, AGATA will benefit from the increased selectivity of ancillary detectors currently developed in the framework of new facilities (SPIRAL2, SPES, FAIR). AGATA will be coupled to the next generation of neutron detectors NEDA (see Figure 16), to the charged particle detector DIAMANT and MUGAST, developed for ISOL facilities, and the high energy γ-rays scintillator array of PARIS and the fast timing detectors of FATIMA, opening new avenues in the detailed description of the nuclear structure and nuclear reaction mechanisms. In conjunction with site-specific beams, particle separators and spectrometers full exploitation of AGATA's capabilities will become possible.

At FAIR, the high-purity Germanium Array DEGAS will be a key instrument for Decay Spectroscopy (DESPEC) project, which will allow high-resolution spectroscopy from alpha, beta, proton, neutron and isomeric decays of exotic nuclear species. It will employ electrical cooling of the cryostats and it will be surrounded by an active shielding shell.

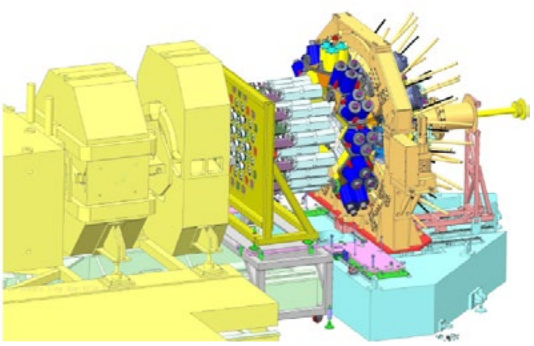


Figure 16. The AGATA array at GANIL, coupled to the NEDA neutron detectors at forward angle and detectors from the neutron wall array at 90°in front of the VAMOS spectrometer.

A number of Ge arrays, most employing conventional anti-Compton shields principle, are available in European Laboratories, contributing to a rich gamma-ray spectroscopy programme in conjunction with ancillary detectors (e.g., EXOGAM (GANIL), GALILEO (LNL), JUROGAM (JYFL), MINIBALL (ISOLDE), ORGAM/NuBall (Orsay), ROSPHERE (Bucharest), ELIADE (ELI-NP), EAGLE (Warsaw)).

Scintillator detectors still cannot compete with Ge in terms of energy resolution, even with the use of new materials (e.g., $LaBr_3$:Ce). However, in all physics cases where time resolution, efficiency for medium and high energy gamma-rays, and fast charged particle identification are needed, scintillators arrays are commonly used. In Europe, several scintillator arrays exist or are under development: they can work in standalone configuration or in complex setups comprising different of detection systems. Arrays of smaller (few inches) scintillators are employed for lifetime measurements, in the ps to ns range (e.g. FATIMA), while large volume detectors are ideal for high energy γ-rays (e.g., HECTOR+, ELIGANT-GN, PARIS, OSCAR), fast charged particles and γ rays (CALIFA).

Particle Detectors

Challenges in nuclear structure and dynamics require charged particle detectors capable of identifying particles, and to measure their energy and emission angle with the highest precision. Nuclear dynamics studies profit from powerful 4π or large area detector systems such as Chimera, Indra and the combined array GARFIELD+RCO, operating at the INFN-LNS, GANIL and INFN-LNL laboratories, respectively. Charge and mass identification is attained by means of energy loss, time of flight and pulse-shape measurements in different detector materials, including silicon, inorganic scintillators and gas detectors. Direct reactions aimed at precise spectroscopic measurements require high energy and angular resolution. These features are encountered in double-sided silicon detectors equipping extensively used arrays such as MUST2, Tiara and Charissa. New generation arrays are under construction to address the most ambitious technical challenges with future radioactive and stable beam facilities. Notable examples are the FAZIA array for nuclear dynamics at intermediate energies (made of high uniformity nTD silicon detectors and CsI(Tl) crystals), and the GASPARD and TRACE 4π and highly segmented nTD silicon strip and pad arrays, to be used in coincidence with γ-ray detectors. These systems are characterised by digital and high speed pulse-shape capabilities, with charge and mass identification over a wide dynamic range (4 GeV for particle charges Z~1-50, in FAZIA, and 50-200 MeV for Z=1-2, in GASPARD and TRACE). Low energy identification thresholds are ensured, an important feature at RIB facilities. Digital pulse-shape technologies are also implemented in the silicon strip and CsI(Tl) FARCOS detector, at INFN-LNS, for multi-particle correlation measurements and they are successfully used in the KRATTA array, in experiments at both low and very high beam energies. A fast reset ASIC coupled to a stack of double sided Si detectors has been realised for AIDA, the implantation detector for DESPEC at GSI/FAIR.

Calorimetric low temperature detectors (Bolometers) offer excellent opportunities within the NuSTAR project owing to their excellent energy resolution and linearity for heavy ion detection.

Neutron Detectors

There exist efficient detectors for slow and for high-energy (above 100 MeV) neutrons, whereas neutrons in the range of a few MeV's still present a challenge. Very specialised instrumentation exists for experiments taking place at reactors and spallation neutron sources. For low-energy reactions the focus is on efficiency, on the capability to distinguish neutrons from other radiation, such as γ rays, and for detector arrays on eliminating cross-talk between modules. Several improved specification arrays are being constructed at the moment (e.g. NEDA). For high-energy reactions neutron arrays are an essential and integral part of complete kinematics setups, one clear example being NeuLAND for the R^3B setup.

Active Targets

Gaseous detectors are well-suited for the study of the most exotic nuclear species thanks to their efficiency and versatility. When used as vertex trackers, thick targets can be employed (as target and detector) without loss of resolution, in particular for low-energy particles. Large interest in these devices has grown worldwide over the last few years, with a number of instruments being built. Progress has been made especially with the increase of their dynamic range, by using various mechanical and electronic methods. Another key development has been in dedicated digital read-out electronics, handling the large number of pads present in some of the detectors. In Europe, recent efforts for a new generation of active targets concentrated around the ACTAR TPC (GANIL-based active target and TPC chamber) from which other projects have originated. The physics scope of active targets is broad, including direct reactions (elastic and inelastic scattering, one and two-neutron transfer), resonant reactions, inelastic scattering with low-momentum transfer and, exotic decay modes. Active targets are planned at the forthcoming RIB facilities of HIE-ISOLDE, SPES, SPIRAL2 and FAIR and at the gamma-ray beam facility ELI-NP.

Hadron spectrometers

Novel detection and measurement schemes are presently under development for new experiments exploring nucleon resonances and strangeness in exotic nuclei as well as mesonic atoms. Different options (e.g. solenoid-type or dipole magnet based systems) for meson and light hadron identification and spectroscopy (by tracking and time-of-flight measurements) are under development. It is planned to use these detectors for invariant mass spectrometry together with the high-momentum resolution capabilities of high-energy spectrometers like FRS or Super-FRS. This is an emerging field, which will open up new degrees of freedom for exotic nuclei research.

Storage rings

Storage rings are well-established instruments in atomic, nuclear and high-energy physics and with them quite remarkable discoveries were achieved. The combination of the fragment separator FRS and the experimental storage ring ESR of GSI was the first incarnation of experiments with radioactive beams in storage rings. This, together with new technical features such as electron cooling of heavy ions, provided unprecedented physics opportunities and novel results. Despite the challenging techniques and instrumentation, the obvious potential for basic science prompted plans and developments at many other facilities worldwide. Today, a major activity is the construction of the storage-ring complex at GSI/FAIR. At HIE-ISOLDE, there are plans to install a storage ring, which will be the first of its kind at an ISOL facility, thus underlining the pioneering role of Europe in this domain. It will open new possibilities in atomic, nuclear, nuclear astrophysics and neutrino physics. The CERN Scientific Policy Committee strongly supports the physics case.

With respect to in-flight separation and storage rings for high beam energies, the construction of FAIR is underway and awaits its completion. At the Collector Ring (CR), where secondary ion beams undergo stochastic pre-cooling, direct mass measurements of extremely short-lived nuclei (down to half-lives of the timescale of microseconds) far off stability can be performed with high accuracy using Isochronous Mass Spectrometry (ILIMA). The New Experimental Storage Ring (NESR) serves several precision experiments with exotic ions and antiprotons. It will be equipped with stochastic, electron and laser cooling and comprise several straight sections for dedicated detector systems and internal targets (including an eA-collider with a counter-propagating multi-MeV electron beam) for a variety of experiments including very low-energy experiments (like direct reactions). As novel features at FAIR, the implementation of storage-rings will enable measurements of hadronic scattering at low momentum transfer (EXL), electron scattering off exotic nuclei (ELISE) and fission studies with radioactive beams (ELISE). In an intermediate stage, the existing ESR of GSI and the new high-energy storage ring HESR, which is part of FAIR modular start version, will provide unprecedented and world unique opportunities. In particular, the highly-relativistic beams (gamma up to ~6) accelerated in the HESR synchrotron, open up a new domain, never before explored with radioactive beams.

Traps and Lasers

Atomic physics precision techniques have been used for decades to extract information of nuclear levels and the rapid introduction during recent decades of novel techniques for ion manipulation has given new physics possibilities.

Laser ionisation sources are increasingly favoured for production of ISOL beams due to their significantly enhanced selectivity. Apart from decreasing the level of contaminants it also, in favourable cases, allows “in-source” physics to be performed, such as the recent measurement of the ionisation potential of the rare element astatine.

Laser spectroscopic measurement on ionic or atomic beams and mass measurements in ion traps yield the state-of-the-art information on nuclear masses, radii and moments and are therefore implemented at many radioactive beam facilities worldwide. The techniques are being continuously refined, with ISOLDE leading the scene in Europe. Recent additions include a cooler-buncher (pioneered in JYFL) that increased the sensitivity of collinear fluorescence spectroscopy by two to three orders of magnitude, the development of a dedicated collinear resonance ionization spectroscopy beamline which further improved the sensitivity with another two orders of magnitude, and the installation of a multi-reflection time-of-flight mass spectrometer that allowed mass measurements of the Ca-chain at ISOLDE all the way out to ^{54}Ca.

In-gas-jet resonance ionisation spectroscopy is the latest addition to this family of techniques, combining the efficiency of in-source method with enhanced resolution thanks to the reduction of Doppler broadening. A set-up such as this is planned for research on elements around and beyond uranium at the S3 facility of SPIRAL2.

Technical Innovations

Electronics - The new detection setups in nuclear structure research pose a number of challenges on the associated read-out electronics including a large number of channels, large dynamic ranges, low noise and high energy and timing resolution, and high throughput. Digitisation of signals has become the norm for most detectors, complemented with high-density front-end electronics based on Application-Specific Integrated Circuits, multiplexing of the signals and solutions for back-end electronics based on existing standards from Telecommunications Computing Architecture. The trend is towards triggerless systems and time-stamped signals.

Several dedicated systems have been developed, while only a few flexible systems with a wider scope exist (FEBEX and GET are two notable examples). For the future, the development of a common platform allowing the integration of the various existing and planned detection spectrometers is one of the objectives of the EURISOL DF.

Scintillators - The last few years have seen fast developments in scintillator detectors owing to the availability of i) new scintillation materials, ii) high efficiency photocathodes, iii) new photo-sensors, iv) new configurations or designs and v) fast high bits digitisers.

Some materials are nowadays well established ($LaBr_3$:Ce), some are in an advanced state of test or already used ($CeBr_3$:Ce or SrI2) and some are still in the prototypal phase (CLYC, GYGAG, CLLB or CLLC). In addition, the development of super-bialkali photocathodes and the impressive evolution of SiPMT granted scintillation detectors better performances, immunity to magnetic fields and imaging features.

Training the next generation of researchers in nuclear physics

Strong connections between universities, research laboratories and institutes worldwide are essential in order to create a unique training ground for the future needs of nuclear physics.

Over the last years, the TALENT (Training in Advanced Low-Energy Nuclear Theory) initiative has developed an advanced and comprehensive training for graduate students and young researchers in low-energy nuclear theory. This effort encompasses a broad curriculum that provides the platform for a cutting-edge theory for understanding nuclei and nuclear reactions, available to early-stage researchers in Europe and worldwide. The educational material, generated by experienced teachers, is collected in the form of web-based courses, textbooks and a variety of modern educational resources. It enables smaller university groups to profit from the best expertise available. This initiative is partly based on the success of more experiment-devoted schools such as the Euroschool on Exotic Nuclei or the International Joliot-Curie School.

TALENT provides students in theory and experiment with a broad background in methods and techniques that can easily be applied to other domains of science and technology. This knowledge is crucial not only for a basic understanding of nuclei, but also for further development of knowledge-oriented industry, from nanotechnology and material science to biological sciences and to high performance computing. As such, TALENT provides interdisciplinary education when it comes to theories and methods.

Recommendations

Radioactive ion beam facilities

The pillars of the RIB facilities network in Europe will be based on both in-flight separation and the ISOL approach.

The urgent completion of FAIR, with the wide and unique programmes on nuclei far from stability at NUSTAR with the SUPER-FRS and its instrumentation, are of utmost importance for the community. It is also important that the upgraded GSI facility will continue to perform a science programme and instrumentation commissioning during Phase 0 of FAIR.

The highest priority and resources should be provided to allow the aims of the major ISOL facilities (SPIRAL2, HIE-ISOLDE and SPES) to be achieved, including their associated innovative instrumentation. The successful completion and exploitation of these facilities will form a major step along the path to the ultimate ISOL facility, EURISOL. This first step along the path can be taken within the framework of the EURISOL-DF facility, naturally leading to strong synergies addressing challenging questions in nuclear science at the European level.

Stable ion and photon beam facilities

Completion and operation of the unique ELI-NP facility is recommended. Its scientific programme with new and unique probes (high power lasers and brilliant gamma-ray beams used also for an IGISOL facility) should be supported.

Full support should be given to existing stable beam facilities offering transnational access within the ENSAR2 H2020 project (ALTO, GANIL, GSI, IFIN-HH, JYFL, KVI-CART, LNL-LNS and NLC). In particular, the very high-intensity stable-ion beams from LINAG (of SPIRAL2), the superconducting cw-linac under construction at GSI, and the SHE factory at Dubna offer exciting opportunities especially in the field of superheavy element research.

Other small and medium scale facilities, often university based, should be supported for their specific programmes, for the development of new instruments and also to provide education and training of the next generation of researchers.

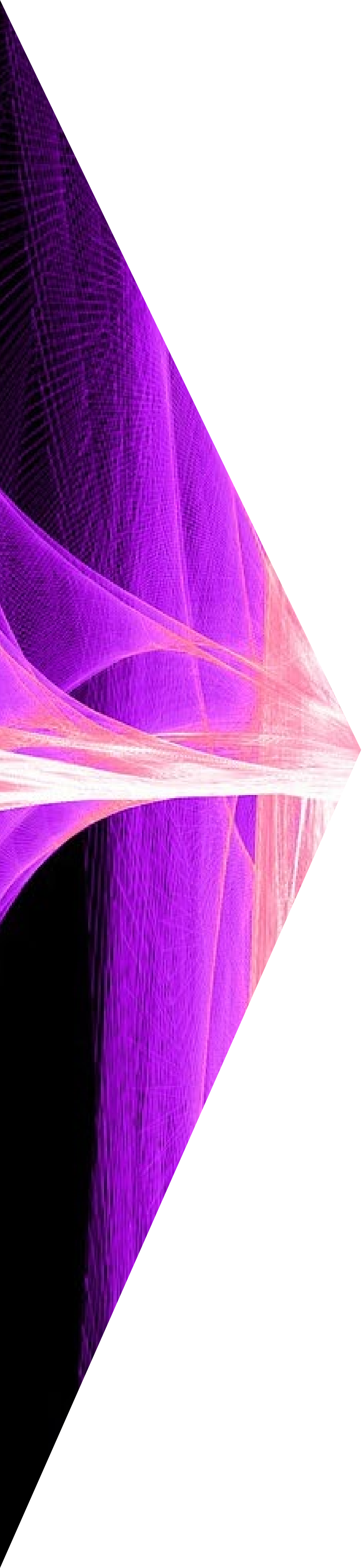
Instrumentation

The radioactive and stable beam facilities host a large variety of state-of-the-art instruments, the development and realisation of which are essential in order to optimally exploit the available beams.

A particular flagship is the gamma-ray spectrometer AGATA. The timely completion of the full AGATA spectrometer and the provision of adequate support and maintenance are of the highest importance to address the exciting science programme at both the stable and radioactive beam facilities.

Theory

Support is needed for theory focusing on a universal description of nuclear structure to provide bridges between the ab-initio, shell model and EDF methods. Effort should be made to integrate reaction dynamics and nuclear structure so that the input required for reaction calculations is based on state-of-the-art structure calculations. The challenge of interpreting the extraordinary variety of nuclear data requires expansion of the theory community in terms of available manpower and also in available computational resources.



4

NUCLEAR ASTROPHYSICS

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4. NUCLEAR ASTROPHYSICS

INTRODUCTION

The world around us is intimately linked with the properties and reactions of atomic nuclei. From the sunlight that supports life, to the silicon integrated circuits in our computers, from the lives and deaths of stars to the evolution of the Galaxy, from processes that operate at femtometer scales to structures that stretch across thousands of light years, it is nuclear physics that has shaped the Universe. As such, progress in *nuclear astrophysics* requires not only experimental and theoretical nuclear physicists, but also the collaborative effort of astronomers, astrophysicists and cosmologists. And the challenges ahead will require state of the art experimental, theoretical, computational and observational capabilities.

Today, terrestrial telescopes are complemented by a fleet of space observatories, each delivering vast amounts of data, and collectively surveying all parts of the electromagnetic spectrum. This is further supplemented with neutrino, cosmic-ray and gravitational wave observations. Embedded in these data is information on the properties and evolution of individual stars, the signatures of stellar explosions, and the history to the beginnings of the Universe. These multi-messenger signals allow us to benchmark and test the predictions of astrophysical models, with nuclear physics a pivotal ingredient.

Technological advances in computation now allow us to model stars and stellar explosions in three dimensions. These multi-dimensional simulations have emerged as a new approach over the past two decades. Their advantage is that they offer a consistent description of fluid dynamics and avoid artificial symmetry assumptions, meaning more accurate modelling of the effects of rotation, mixing processes, changes to the interior structure of model stars, and the nuclear physics processes therein. This comes at the price of complexity and higher demands on computational resources. Progress in this field is thus linked to the implementation of advanced numerical techniques and to the growth of supercomputer power.

The building blocks of matter are nuclei. Nature has supplied the Earth with about 300 stable or long-lived radioactive isotopes that may be studied in the laboratory. However, a much greater variety of mostly unstable isotopes are produced during stellar explosions. Radioactive beam accelerator facilities provide access to an increasing number of these exotic nuclei. With current, and future generations of facilities we can study the properties of, and reactions among, these rare isotopes, to give us insight into the nuclear processes that synthesise elements.

Which nuclear properties are relevant for the description of a particular astrophysical process depends on the environmental conditions. Nuclear theory is then fundamental in connecting experimental data with the finite temperature and high-density conditions in a stellar plasma. Advances in the description of the nuclear interaction, based on the symmetries of quantum chromodynamics together with novel many-body techniques, allow for parameter-free calculations of reactions relevant for stellar burning. Unified approaches for light-towards-heavy nuclei will allow for theoretical predictions with uncertainty estimates relevant to the description of explosive scenarios.

The recent detection of gravitational waves opens another window on the Universe. Gravitational waves probe extreme conditions of matter densities that electromagnetic signals cannot elucidate, but within which nuclear physics undoubtedly plays key roles. New demands will be placed on nuclear astrophysics, requiring innovative techniques and interdisciplinary approaches.

Nuclear physics is therefore crucial for the understanding of the evolution and explosion of stars, the chemical evolution of the Galaxy and its assembly history. It contributes to key science questions:

What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?

Where are the building blocks from which is life created?

How do nucleosynthesis processes evolve with time?

What is the nature of matter under extreme conditions? Can multi-messenger observations provide access to conditions not reached at present laboratories?

In this chapter, we will outline the current state of knowledge in nuclear astrophysics, highlight the future directions of the field and provide recommendations and priorities.

THE LIFE CYCLE OF MATTER

Cosmic gas collects under gravitational attraction into higher density regions, eventually forming stars of a variety of masses. These stars are stabilised against further contraction by the release of nuclear binding energy in their interiors. Nuclear fusion reactions process isotopes of light elements, such as hydrogen, into iron nuclei, where nucleons are most tightly bound within the nucleus. The precise sequence of nuclear reactions, and their rates, depends mainly on the initial mass of the star. Low-mass stars remain in such an equilibrium between gravity and nuclear heating for a time comparable to the age of the Universe, while for massive stars it takes just a few million years for an iron core to form, and gravitational collapse to a more compact form ensues. Such gravitational collapse typically leads to a supernova explosion, ejecting large amounts of stellar gas back into space. This stellar gas, ejected from the supernova, has now been enriched with the products of the nuclear fusion reactions. A second generation of stars may then form from this gas. Their evolution proceeds as above, but with modifications due to the change in initial composition. Such is the cycle of cosmic matter, which successively enriches cosmic gas from its initial Big Bang composition to one rich in the variety of elements we observe - and that are the prerequisite to life on Earth. Additional contributions to such "chemical evolution" of cosmic gas arise from stellar winds and from nuclear processes and explosions on the surfaces of compact stars such as white dwarfs. These then also contribute in different but specific ways to the composition of the interstellar medium.

In the following we present what is known about the different stages and sites of nuclear processing of cosmic matter, starting from the Big Bang, then through stars and their explosions.

Big Bang nucleosynthesis

The standard model of cosmology and particle physics provides our current best physical description of the Universe. Two important predictions of this model have been experimentally confirmed: the production of the lightest elements during the first minutes after the Big Bang, known as Big Bang Nucleosynthesis (BBN), and the existence of a relic cosmic microwave background (CMB). Within the standard BBN (SBBN) the abundances of the four light nuclei ^{2}H(D), ^{3}He, ^{4}He, and ^{7}Li depend on the density of baryonic matter, Ω_b, and on the expansion rate of the Universe. The latter depends on the effective number of neutrino species where the standard model value corresponds to N_{eff}(CMB) = 3.046. Deviations from this value could indicate new physics not presently captured by the standard model. The most precise measurements of these quantities are due to the careful analysis of the CMB anisotropies, recently measured with exquisite detail by the Planck collaboration. Their analysis gives N_{eff}(CMB) = 3.04 ± 0.36, consistent with the standard model predictions. However, as CMB and BBN probe different epochs of the Universe, there could be new physics that operates at the BBN epoch and not necessarily during the phase of photon decoupling that shapes the CMB. It turns out that the primordial abundance of D is sensitive to the baryon density while the mass fraction of ^{4}He depends strongly on N_{eff}. Precise measurements of the primordial abundances of these elements can provide important constraints on those parameters within the context of SBBN. Indeed, SBBN calculations based on the CMB parameter values reproduce with unparalleled precision the measurement of the D/H ratio. However, the latest measurements of the mass fraction of ^{4}He tentatively suggest N_{eff}(BBN) > N_{eff}(CMB). This conclusion may depend on systematic differences in the analysis strategies of ^{4}He observations. It is expected that in the near future high-resolution data on ^{4}He emission lines will further reduce the uncertainties in primordial helium determination. Alternative probes such as the ^{3}He/^{4}He ratio are being pursued to address possible systematic uncertainties in the ^{4}He ratio, where the ^{3}He abundances is to be determined from the ^{3}He I flux from nearby low metallicity H II regions.

Nevertheless, to obtain bounds on the relevant parameters from SBBN that are competitive with those of CMB analysis, a further reduction of the uncertainties in the nuclear reactions responsible for the production of D and ^{4}He is necessary. The rates that determine the D/H ratio are $d(p,\gamma)^3\mathrm{He}$, $d(d,n)^3\mathrm{He}$ and $d(d,p)^3\mathrm{H}$. For the He isotope ratio, the most important reactions are $d(p,\gamma)^3\mathrm{He}$ and $^3\mathrm{He}(d,p)^4\mathrm{He}$. Figure 1 illustrates the impact that knowledge of the relevant reaction rates with 1% uncertainty will have on the SBBN predictions. Interestingly, the BBN contours are comparable in size to the latest CMB results. The crucial reaction $d(p,\gamma)^3\mathrm{He}$ has been recently calculated based on an *ab initio* approach that includes two- and three-nucleon interactions and two-body contributions to the electromagnetic current. The calculations predict an increase of 10% in the S-factor at BBN energies with a quoted uncertainty below 1%. Experimental data for the remaining reaction rates are needed.

^{7}Li has the smallest observable abundance

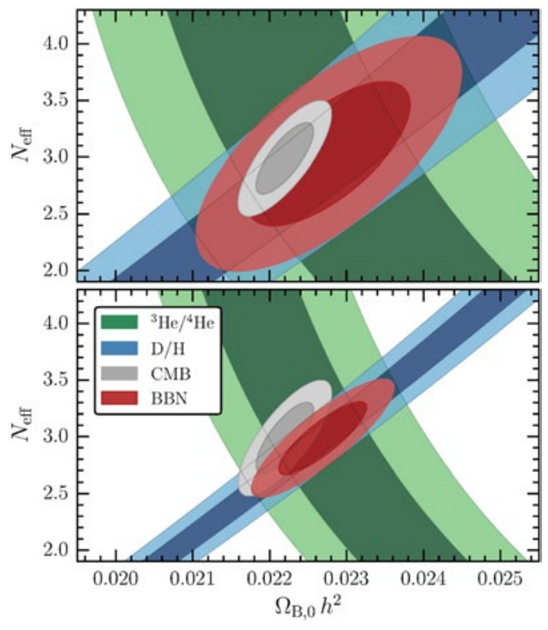


Figure 1 Confidence contours of the baryon density and effective number of neutrino species that reproduce the observed D/H and $^3He/^4He$. The lower panel illustrates the impact of a 1% uncertainty on the nuclear reaction rates. Interestingly, the BBN contours are comparable in size to the latest CMB results. [Adapted from Astrophys. J. 812, L12 (2015)]

predicted by SBBN, but serves as a consistency check on the theory and could potentially be sensitive to physics not captured by the production of the other elements. The main observational signature of primordial Li is the existence of the Spite plateau with very small scatter for halo stars with metallicities down to [Fe/H]~-3. However, observations at lower metallicities show a much larger scatter with stars having Li/H ratios below the Spite plateau ratio. It seems that some halo stars may have destroyed their lithium. Addressing the mechanism responsible may be critical to solve the "lithium problem" in which the observed primordial Li abundance is a factor 3 lower (and 4σ) than the predictions of SBBN. Observations of interstellar lithium in galaxies at low metallicity will help to test the mechanism potentially responsible for its depletion in stars. Nuclear reactions responsible for the production of ^7Li are known to ~10% or better; further improvements are necessary.

It is a possibility that the lithium problem points to new physical processes at play during, or after, primordial nucleosynthesis. The challenge is to find a mechanism that would reduce ^7Li without affecting the other abundances. The recent precise measurement of D/H tightly constrain the allowed range of values, and challenges if not excludes most of the proposed exotic solutions to the lithium problem.

Lives of stars

Stars consist mainly of hydrogen and helium. Nuclear reactions in their interiors are responsible for the synthesis of heavier isotopes and elements, initially burning hydrogen to helium, then helium to carbon, and so forth, until silicon and iron are reached, thus releasing the energy necessary to maintain stability against gravitational collapse. Except for the relatively short periods when there is a transition from one major burning phase to the next, and for the very dynamical final phases, during most of their lifetimes stars are in hydrostatic equilibrium. Nuclear reactions thus are important both for the energy the release and for the elements the produce, and so a detailed understanding of these nuclear reactions is vital.

There are many successes of a spherically symmetric approach to modelling stars, which has culminated in sophisticated codes with detailed microphysics. Some of these codes are open source, opening new opportunities in education. Large grids of stellar models are available that probe the parameter space of initial stellar mass, composition and rotation rates and include rather large nuclear reaction networks for the nucleosynthesis. The existence of these modelling capabilities also facilitates studies of the sensitivity of astrophysical predictions to nuclear physics uncertainties (e.g., heavy element production dependence on neutron capture rates). Models of asymptotic giant branch (AGB) stars are able to explain the abundances of s-process nuclei observed in the Sun, pre-solar grains and galaxies. Models of massive stars that include the physics of rotation with spherically symmetric prescriptions can explain the enhancement of ^{14}N in the early Universe and, thus, the enhanced efficiency of the weak s-process in that epoch. Significant progress has also been made in the theoretical description of stars close to the transition mass between AGB and massive stars and the limit for forming a white dwarf or a neutron star.

However, there remain many challenges: even models that have been validated by observations contain assumptions and approximate physics with numerous free parameters that severely limit their predictive power. Present and future efforts now focus on developing simplified physics models with multi-dimensional simulations and experiments (forward modelling) rather than by calibrating free parameters to the observables they are trying to explain (inverse modelling), as has been done in the past. The common use of multi-dimensional hydrodynamic simulations has taken longer to emerge in the field of stellar evolution (compared to supernova theory) largely owing to the additional challenges of longer time scales, the importance of reaching steady states and the encroachment on the low Mach-number regime, which requires specialised numerical methods. In the last decade alone, 2D and 3D hydrodynamic simulations of stars have already yielded several important results including predictions of: entrainment rates across convective boundaries; pre-supernova velocity fields that are the seeds for neutrino-driven convection in multidimensional core-collapse supernova simulations; and nucleosynthesis in convective-reactive events, able to explain the neutron capture abundance pattern of the post-AGB star known as Sakurai's object

Stellar models should, where possible and appropriate, be validated with observational data. Recent years have seen a plethora of new data against which stellar models may be validated and challenged:

- Asteroseismic observations show that convective cores are larger than predicted by classical convection theory.
- Large binary fractions are found amongst massive stars. Binary interactions influence their evolution and fate.
- The discovery of very massive stars in the local Universe with initial masses up to 320 solar masses (well above the previously accepted upper mass limit of stars around 150 solar masses). This challenges star formation scenarios and opens the possibility of exotic pair-instability supernovae.
- With current large surveys, many faint and fast transients are observed. These so-called supernova impostors provide more constraints and questions about the evolution of stars.
- The Gaia satellite, as well as large ground-based surveys, is now producing extremely large datasets that will place dramatically stronger constraints on stellar populations in the nearby Universe.
- Surveys of metal-poor stars provide key information about the first stellar generations and will continue to challenge the modelling of the first stars, their formation scenarios and the early evolution of the Universe.

In all of these scenarios, nuclear physics has a significant role.

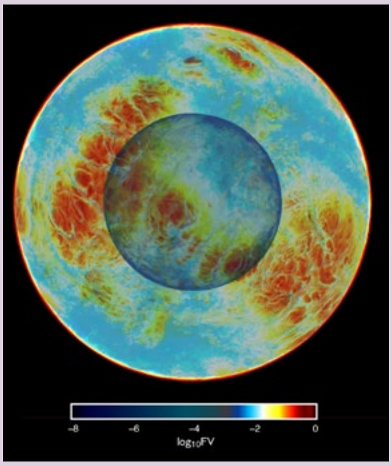
Hydrogen burning

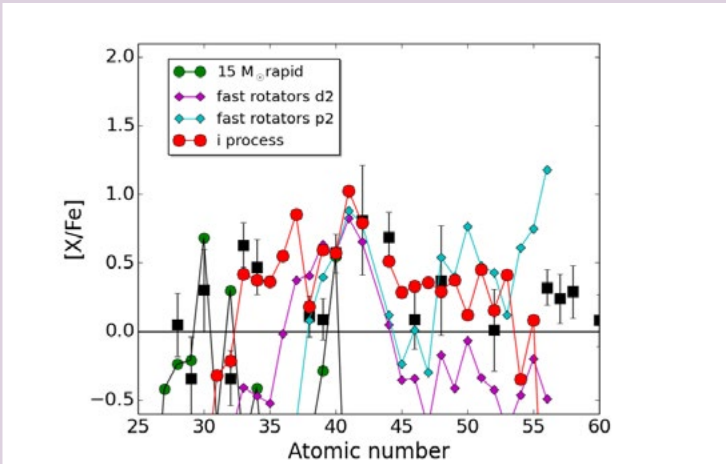
Hydrogen burning is the best understood phase of stellar evolution, particularly in low mass stars. This is due to the high quality of multi-messenger data for our Sun, including elemental abundance observations of the solar atmosphere, helioseismic waves that probe the solar interior and neutrino observations that provide a direct snapshot of the nuclear reactions in the Sun's core. The observation of neutrinos from the Sun was one of the scientific milestones from last century and has been the recipient of two Nobel prizes (2002, 2015), the latter being awarded to the SNO collaboration for the direct confirmation that neutrinos produced in the Sun change their flavour as they travel to Earth. This was the final resolution to the "Solar Neutrino Problem" that started with the pioneering experiment of Ray Davis in 1968. Nuclear astrophysics played a fundamental role in solving the problem by providing ever-more accurate predictions of the solar fusion cross sections. These improved predictions came as a result of combined high precision experiments and theoretical advances. Thanks to these advances, and based on the measurement of the ^{8}B solar neutrino flux, we have been able to determine the temperature in the Sun's core with a precision of 1%. Similarly to the situation in BBN, solar modelling is entering a precision era. At present, all neutrino fluxes from the pp-chain reactions have been measured. This has confirmed our basic understanding of neutrino flavour oscillations in the presence of matter.

The development of sophisticated three-dimensional non-local thermodynamic equilibrium models for the Sun's atmosphere has led to a substantial reduction in the expected abundances of metals (elements heavier than helium), in particular C, N and O, as compared to previous predictions based on one dimensional models. This has created the "Solar abundance problem", in which solar models that incorporate the new abundances have problems reproducing the sound speed profile measured by helioseismic observations. A possible solution comes from the assumption that the solar abundance of metals is not homogeneous and that the surface may be depleted in comparison to the interior. This behaviour is expected due to the diffusion of heavy elements to the solar interior over the Sun's lifetime. It becomes particularly important to address the "solar abundance problem" from the point of view of neutrino observations. Predictions of neutrino fluxes based on the 2011 compilation of solar fusion cross sections do not favour a metal rich versus depleted interior. However,

Box 1: Stellar models in three-dimensions

A major challenge in stellar modeling is the treatment of multi-dimensional effects such as convection and rotation. Three-dimensional models are being developed that explore the role of these aspects in the evolution and explosion of massive stars, and the production of heavy elements by the s- and i- processes. Addressing the combined role of convection, rotation, magnetic fields, binary interactions, and nuclear reactions remains a major challenge in stellar evolution. Precise measurements of a large number of chemical species can play a crucial role to help constrain these complex stellar models.





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Astrophys. J. 821, 37 (2016)

recent theoretical (see Figure 2) and experimental improvements in the key reactions: $p\left(p,e^{+}\nu_{e}\right)d$, ${}^{3}\mathrm{He}\left(\alpha,\gamma\right)^{7}\mathrm{Be}$ and ${}^{7}\mathrm{Be}\left(p,\gamma\right)^{8}\mathrm{B}$ have resulted in changes in the ^{7}Be and ^{8}B solar neutrino fluxes that favour the model with higher metallicity. To further advance in this issue, and to address degeneracies in composition and opacity changes, measurement of the neutrino fluxes for CNO reactions is now needed: this is the goal of the Borexino collaboration. The experimental challenge ahead is a comparison of the Sun's electromagnetic and neutrino luminosities with a precision of 1% compared to the present precision of 7%. This will allow a direct comparison between the energy production rate and energy delivery rate and improve our understanding of energy transport in stars. It will also put strong constraints on neutrino flavour oscillations to sterile flavours.

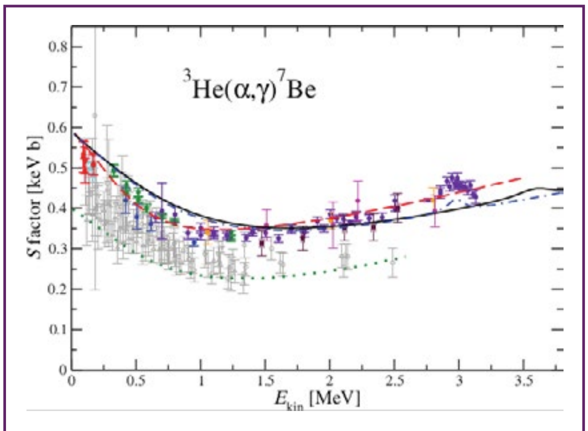


Figure 2: Parameter free ab-initio calculations are now possible for key astrophysical reactions involving light nuclei. This figure shows comparison of experimental data to recently published ab-initio calculations for the ^{3}He(α,γ)^{7}Be reaction. This radiative-capture process is essential for both the primordial ^{7}Li abundance calculations and for ^{8}B neutrinos in the standard solar model. [Phys. Lett. B 757, 430 (2016)].

Helium burning

Stellar fusion of helium is a key bottleneck in producing elements heavier than helium. The reaction is hindered because it proceeds through the (almost) simultaneous fusion of three helium nuclei. The three-particle nature of this process, the triple-alpha process, makes experimental investigation of the reaction extremely difficult. At the temperatures of most helium-fusing stars, the reaction proceeds in two steps: the formation of a very short-lived ^{8}Be nucleus, and then the capture of another alpha particle to form an excited state in ^{12}C known as the Hoyle state, named after Fred Hoyle who proposed the necessity of the resonance and was instrumental in its experimental discovery.

The reaction and the detailed properties of the Hoyle state remains the focus of both theoretical and experimental investigation. Key advances have, over the past decade particularly, included detailed theoretical studies of the three-body dynamics of the reaction at very low temperatures, where the stellar scenarios do not have sufficiently high temperature to populate the Hoyle state. Contrasting this, experimental searches for a key rotating mode of the Hoyle state have been carried out using a variety of nuclear probes: reactions, decays and absorption. At the highest stellar temperatures, the resulting resonance could dominate the helium-fusion process.

The creation of carbon and oxygen in the Universe is fundamental to our understanding of the origin of life on Earth and the life cycle of stars. A key ingredient is precise knowledge of the reaction rate of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, which so far has eluded both theory and experiment. From a theoretically perspective it is very challenging due to contribution of numerous underlying mechanisms. Experimentally there has been more success, but the small cross section requires direct measurements at the limit of current state of the art techniques. Indirect techniques, mainly via β-delayed α emission spectra of ^{16}Nand transfer reactions have contributed to significantly reduce the uncertainty at the astrophysical relevant energies. Measurements of the total capture rate are planned that will have similar precision. Particularly important is the determination of the ground state cross section.

Advanced burning phases

Once helium burning has halted, the core is made mostly of carbon and oxygen with small amounts of heavier elements. The next burning regime proceeds through the fusion of two carbon nuclei to neon and sodium. The rates of these carbon fusion reactions are crucial for determining whether stars proceed on to carbon burning or become CO white dwarfs. These reactions are also important for understanding the triggering of thermonuclear supernovae (type Ia). Due to their extremely low cross sections, direct measurements of these reactions are very challenging and to-date no data are available across the relevant energy range. Recent progress has been made in developing the experimental techniques for studying these reactions, and indeed, these reactions are now key goals of the upgraded LUNA facility. After carbon burning, massive stars go through three more burning stages: neon, oxygen and silicon burning. The case of oxygen burning is very similar to carbon burning since it proceeds by the fusion of oxygen into silicon, phosphorus and sulphur. Neon and silicon burning proceed via a combination of photodisintegrations and alpha-particle captures. Furthermore, weak interactions play an increasing role. Deleptonisation is the key process that facilitates the onset of collapse. While these phases have been studied extensively in spherically symmetric models, effort in the last decades has begun to study these in multi-dimensional hydrodynamics simulations. These simulations show enhanced mixing, and suggest asymmetries in the collapse that might aid successful explosions. Future simulations need to investigate in more detail the interplay between convective mixing and nuclear reactions since extra mixing changes energy generation and small variations of endothermic reactions (for example photo-disintegrations) affect turbulent flows.

Neutron capture nucleosynthesis

The elements from carbon to iron are produced by charged particle reactions during the stellar evolutionary phases from helium to silicon burning. On the other hand, most elements heavier than iron are essentially built up by neutron capture processes. Environments with low neutron fluxes exhibit distinctly different physics to those with high neutron fluxes, as described below.

The s-process

The slow neutron capture (s-) process takes place during helium and carbon burning and is characterised by comparably low neutron densities, typically 10^8 – 10^{10} cm^{-3}. Neutron capture times are therefore much longer than most β-decay times and the reaction path therefore follows the valley of stability. An important consequence is that neutron capture cross sections, averaged over the stellar neutron energy spectrum, are of pivotal importance for the determination of s-process driven abundances. Additionally, the r-process abundances (see below) are defined by subtracting the computed s-process abundances from the solar system abundances.

The main s-process operates in the late phases of low-mass AGB stars and is responsible for the production of half of the elements heavier than iron. The main neutron sources are $^{13}C(\alpha, n)$, with a smaller contribution from $^{22}Ne(\alpha, n)$ for more massive AGB stars. $^{13}C(\alpha, n)$ is active in the so-called ^{13}C-pocket, the formation and evolution of which is still uncertain and thus an active area of research, particularly regarding the impact of rotation and magnetic fields.

The weak s-process takes place in massive stars during core helium and shell carbon burning phases. The main neutron source here is $^{22}Ne(\alpha, n)$. Recent models including the effects of rotation produce large amounts of primary nitrogen and ^{22}Ne, which enables a significant production of elements up to barium at low metallicities (where none was expected from non-rotating models). These effects can explain the large observed scatter in the strontium versus barium ratio in carbon enhanced metal poor (CEMP) stars.

Present experimental s-process studies focus on the measurement of several branching point nuclei, where competition between neutron capture and β-decay yields a local isotopic abundance pattern, which is also strongly influenced by the physical conditions of the s-process environment. In general, both reaction branches need to be known with sufficient precision, but usually it is the neutron capture branch that is most in need of experimental improvement. A few of these difficult measurements have been successfully carried out over the stellar energy range of interest using the corresponding samples of radioactive material, both by means of activation (^{60}Fe, ^{147}Pm, etc.) and time of flight (TOF) measurements (^{63}Ni, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{151}Sm, ^{171}Tm or ^{204}Tl). Thus valuable information has been obtained on the thermal and density conditions of the environment, as well as the timescales of the different evolutionary stages. Nevertheless, some 10-to-20 relevant branching nuclei remain to be measured due to the difficulties inherent in the production of a suitable capture sample, and to the limitations of the radiation detectors used for this kind of measurement. As significant improvements in neutron capture rates are being made, the stellar β-decay rates also become important subjects of experimental s-process research. Moreover, stellar decay rates can differ from terrestrial rates by orders of magnitudes. These effects can and should be investigated in ion storage rings (bound-state beta-decays) or in inverse kinematics applying charge-exchange reactions.

The r-process

The rapid neutron capture (r-) process is perhaps the least understood nucleosynthesis process. It occurs over a vast range of rapidly changing physical conditions, and involves more than 5000 nuclear species. The main reactions include neutron capture and β-decay of unstable neutron rich isotopes. As most of them are theoretically inaccessibly they have to be modeled theoretically based on experimental nuclear masses whenever available. Fission is expected to contribute in environments involving large neutron densities such as neutron star mergers. For this reason, state-of-the-art r-process network calculations have to rely, to a very large extent, on nuclear and decay properties derived from theoretical models. Thus, the calculated abundance patterns exhibit uncertainties that are much larger than those obtained from spectroscopic observations. This significantly hinders efforts to determine the properties of the, so far, unidentified astrophysical site(s) of the r-process based on nuclear physics constraints.

UV spectroscopy surveys made with HST/STIS and ground-based telescopes have provided abundances for nearly every element from hydrogen through to bismuth in most metal-poor stars. These studies give new insight to the stellar nucleosynthesis occurring in the earliest generations of stars, yield accurate constraints on the r-process, and offer a unique opportunity to understand the chemical evolution of our Galaxy. Combined with observations of dwarf galaxies and the sea floor abundance of ^{244}Pu, there is growing evidence that the r-process is associated with rare high yield astrophysical events. From the experimental side, recent surveys at RIKEN (Japan) exploiting high-current cyclotrons have provided beta-decay half-lives for many r-process nuclei around N=82, with a direct impact on r-process abundance calculations. Important advances have also been achieved at GSI, JYFL and ISOLDE through mass and spectroscopic measurements around N=82, including the two key r-process nuclei ^{130}Cd (see Figure 3) and ^{128}Pd. These data have contributed to the solving of the long standing issue of shell-quenching around N=82

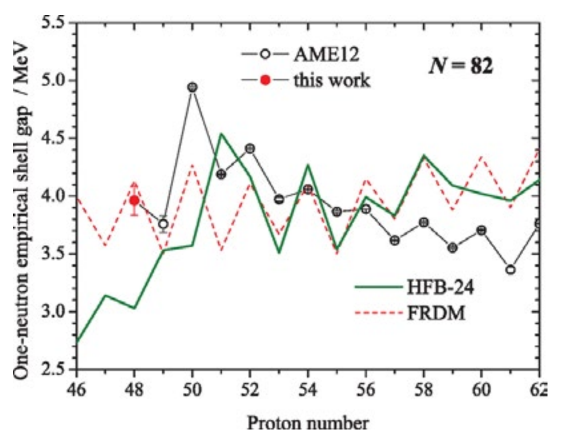


Figure 3: Masses adjacent to the r-process waiting point nucleus ^{130}Cd have been measured with the ISOLDE/CERN Penning-trap spectrometer, ISOLTRAP. They provide important constraints on the evolution of the N=82 shell gap and the production of A = 127-132 nuclei by the r process [Phys. Rev. Lett. 129, 232501 (2015)]

and have led to dramatic improvements in shell-model calculations around this region.

Advances in astrophysical modelling have clarified the likely candidates for the r-process astrophysical site. Neutrino-driven outflow from a hot neutron star, formed after a core-collapse supernova explosion, has long been a leading candidate. However, advances in the description of neutrino-matter interactions, and its implementation in Boltzmann radiation transport codes, have shown that most of the ejected material is proton-rich or only slightly neutron-rich and so do not allow for a strong r-process. Nevertheless, neutrino driven winds remain a likely candidate to produce elements around A~100 by a combination of weak r-process and/or -process.

The merger of two neutron stars (NS-NS) and neutron star – black hole binaries (NS-BH) constitutes at present the most likely source to account for most of the r-process material in the Galaxy. Several binary pulsar systems have been observed. The secular variation of their orbital period agrees perfectly with general relativistic predictions for the emission of gravitational waves and in fact provided the first indirect evidence for gravitational waves, years before the recent direct detection by LIGO/VIRGO. While this first direct detection was from a system of two black holes, a detection originating from a NS-NS or NS-BH merger is expected soon.

Nuclear physics is expected to play a major role in in the interpretation of gravitational wave signatures. First, the partly unknown properties of the high-density equation of state strongly affect merger dynamics and thus the gravitational-wave signal of such events. In turn, this offers the possibility of inferring equation-of-state (EoS) properties from a future gravitational-wave measurement. Already, progress has been made in understanding the EoS dependence of the gravitational wave signal of compact mergers. For instance, the late inspiral phase, where finite-size effects influence the phase evolution, carries an imprint of the equation of state. Also, the frequencies of the oscillations of the post-merger remnant are characteristic of the EoS. These effects highlight future possibilities of constraining the high-density matter EoS. For instance, a measurement of the dominant post-merger oscillation frequency from a near-by merger may allow the determination of neutron star radii with a precision of about 200 meters.

A second role will be in understanding merger contributions to r-process nucleosynthesis. This consists both of material ejected dynamically during the merger and outflows from the accretion disc around the central remnant. The properties of the dynamical ejecta depend on the nature of the merger, NS-NS vs. NS-BH, and its mass asymmetry. NS-BH and asymmetric NS-NS systems are expected to eject cold very neutron-rich material originating from the crust of the neutron stars. This material constitutes an ideal site for r-process nucleosynthesis where fission rates and yields of superheavy nuclei determine the final abundances. In the case of almost equal mass NS-NS mergers, the ejected material originates from the contact interface between the stars. This material is shock heated to high temperatures and weak interaction processes can potentially drive the originally very neutron rich material to only moderate neutron rich conditions. The final impact on r-process nucleosynthesis is not yet fully understood and depends on the finite temperature behaviour of the equation of state.

The accretion disk properties and nature of the ejecta depend on the central compact object: promptly formed BH or a long lived hyper-massive NS. In both cases, the disc can generate outflows on timescales much longer than the orbital time with a contribution to the total mass ejection comparable to or even larger that of the dynamical ejecta. Neutrino heating is sub-dominant when the central object is a BH. The outflow is powered by angular momentum transport and nuclear recombination. Present models suggest ejecta is moderately more neutron-rich than the dynamical ejecta, with a nucleosynthesis yield in agreement with observations of metal-poor stars (see Figure 4). Neutrino heating is much more important if the merger produces a long-lived hyper-massive neutron star, resulting in a larger ejected mass with higher proton fraction.

Mergers constitute the most likely scenario where r-process nucleosynthesis might be observed in situ. The amount of ejected material in a single event is relatively large since the energy liberated by radioactive decay can drive an electromagnetic transient known as a kilonova. Kilonova light curves are expected to reach maximum luminosity on timescales of a week. A kilonova event has likely been recently observed associated to the short gamma ray burst GRB 130603B. In addition to providing a direct probe of the formation of r-process nuclei, kilonova observations provide a unique diagnostic of physical processes at work during the merger. This will be particularly important – and exciting - if a future observation is seen to be associated with a gravitational wave detection.

Addressing the impact of mergers in r process nucleosynthesis requires the contribution of both dynamical and disk ejecta to be considered. Individually or in combination, they may contribute to the production of the whole

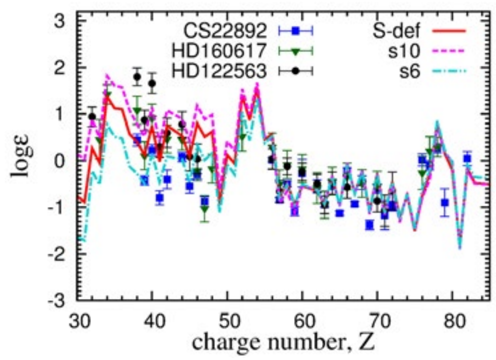


Figure 4: Compact binary mergers have the potential of accounting for the observations of r-process elements in metal-poor stars [Mon. Not. Roy. Astron. Soc. 463, 2323 (2016)]

range of r process nuclides. The frequency and delay time from formation to merger remains an open issue. Gravitational wave detection from neutron star mergers will provide direct constraints to the merger rate of the present-day universe. However, the merger rate and/or delay time may not be enough to account for the early r process enrichment as seen in metal poor star observations. This points to the need of an additional site to account for the production of r process elements in the early Galaxy. A likely candidate are jet driven explosions of massive stars due to a combination of magnetic fields and rotation.

Evidence for additional nucleosynthesis processes

The star known as Sakurai's Object is the dying remnant of an AGB star in which there is still some nuclear activity in a thin He-burning shell lying beneath a layer of hydrogen. A thermonuclear runaway explosion in the helium layer drives the development of a deep convective layer, which engulfs a small portion of the hydrogen layer above. The result is that hydrogen and carbon are periodically brought together under helium-burning temperatures, releasing significant energy in a short period of time. Indeed, this appears to be on a timescale comparable to the convective time scale, which is the time scale on which the energy can be transported away. Therefore, the convection and the nuclear energy releases interact and this is why such events are called convective-reactive.

An interesting consequence of the combustion of carbon and hydrogen at helium-burning temperatures (usually hydrogen has been depleted before helium burning is ignited) is the production of neutrons via the $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C(\alpha,n)^{16}O$ reaction sequence. Spherically symmetric nucleosynthesis models, guided by insight gained from 3D hydrodynamic simulations, suggest that characteristic neutron densities achieved in this scenario lie between those of the s- and r- processes (about The existence of this intermediate-process was suggested long ago but has recently received new attention thanks to improved hydrodynamical simulations and observational evidence. It has been named the "i-process".

Nucleosynthesis simulations of i-process conditions have recently been shown to match the puzzling abundance patterns of a sizeable subset of so-called carbon-enhanced metal-poor (CEMP) stars incredibly well. This agreement is much better than a calibrated blend of s- and r-process-enriched material fitted to the observations, which is the alternative scenario to explain the formation of CEMP-r/s stars. The i-process path of nuclei involves reactions between rather short-lived isotopes for which there are limited experimental data. However, as the i-process path lies closer to stability than the r-process, experimental information on nuclei in the i-process path are expected to be obtainable in the near future.

A tiny fraction of the heavy elements observed in the solar system is located on the neutron-deficient side of the valley of stability, which cannot be synthesised by the neutron capture s and r processes. The astrophysical "p process" responsible for the production of these isotopes is still not well understood, and requires further extensive experimental and theoretical effort. It is generally accepted that the major role in creating p isotopes is played by gamma-induced reactions in hot stellar environments (hence the name γ-process).

The astrophysical site where such a process may take place is still under debate. Encouraging calculations became available recently both for core collapse and type Ia supernovae, but the consistent reproduction of all p isotope abundances is still not possible. The further improvement of p-process models is therefore needed. In addition, there is mounting evidence that deficiencies of the γ process models to account for the large abundances of neutron deficient isotopes of molybdenum and ruthenium do not have a nuclear physics origin. Alternative scenarios for the production of these isotopes have been suggested including the np and ν process.

From the nuclear physics side, the study of the nuclear reactions of p-process relevance is also crucial, as the reliable reaction rates provide the necessary basis for p-process models. As is the case for the r-process networks, owing to the huge number of reactions involved in a p-process network, and the extremely small cross sections, the reaction rates are taken from nuclear theory. Comparison with the available but highly limited experimental database indicates these calculations often perform poorly. The nuclear reaction models must thus be improved, in turn requiring a more extensive experimental database: further experimental investigations of p-process related nuclear reactions are recommended.

In the case of reactions involving charged particles, recent results reveal the predictive power of nuclear reaction models to be especially poor. Cross section measurements of proton- and alpha-induced reactions at low energies are thus of high priority. Measurements can provide direct data for astrophysical models and can provide crucial nuclear parameters. For example, the low energy alpha-nucleus optical potential was found to be in need of substantial improvement. This can be studied by high precision elastic scattering experiments as well as by the measurement of alpha-induced cross sections. Other nuclear parameters, like nucleon-nucleus optical potentials, level densities and gamma-ray strength functions, must also be studied and made more precise. Although their direct relevance to the astrophysical p-process is limited, the usage of high intensity gamma-beams, such as the ones provided by the coming ELI-NP facility, will be useful for the precision study of the gamma-ray strength functions.

Stellar explosions

Supernovae play a crucial role in the synthesis of elements and in the dissemination of the nuclear burning products of stars. The past decade has witnessed the rapid development of multi-dimensional simulations of both main classifications: thermonuclear and core collapse. With the increasing power of supercomputers, an ever-more detailed treatment of the physical explosion processes has followed. Simulations, initially carried out in spherical symmetry or two spatial dimensions, covering all or only parts of the exploding stars, and including predefined initial conditions for some key physics, all have now been developed into three-dimensional full-star models. Advanced multi-D hydrodynamical simulations are very sensitive to the microphysics ingredients. For example, small variations in neutrino interactions may turn an unsuccessful core collapse explosion into a successful one. Consequently, it is important to address and reduce the nuclear physics uncertainties in such simulations.

Thermonuclear supernova explosions have been modelled starting from their observed homogeneity as the evolutionary end of an accreting white dwarf that reaches the Chandrasekhar mass limit. A central ignition is rapid enough to disrupt the star, while nuclear burning reaches nuclear statistical equilibrium and thus leads to production of large amounts of iron group nuclei. Initially, one-dimensional models with an empirical transition from deflagration to detonation were found to describe both explosion and outcome well. More recently, two- and three-dimensional models have been implemented, with the main goals being to capture the flame propagation under degenerate high-pressure conditions, exploring how instabilities, turbulence and their hydrodynamical consequences change the local burning conditions and kinematics. These must retain the observed overall homogeneity, while aiming to recreate the variety of detail that has became clear in the recent large observational surveys. By introducing a transition from deflagration to a detonation that can be motivated from a density gradient mechanism, such models were found to reproduce the observed variations between light curve rise and fall times and the absolute brightness. Thus, these delayed-detonation models seemed a good candidate to explain normal thermonuclear supernovae. Surprisingly, it was then found that an entirely different class of models was also able to reproduce observations: a white dwarf with a mass well below the Chandrasekhar limit in collision with another white dwarf companion, a so-called ‘double degenerate’ event. The non-violent variant of this starts from helium burning and may explain normal thermonuclear explosions, while a violent merger of two white dwarfs may explain variant subtypes.

For thermonuclear explosions therefore, the main achievements of recent years have been: i) the exploration of different explosion scenarios with three-dimensional full-star simulations that avoid tuneable parameters in their description of the explosion physics; ii) the determination of the nucleosynthetic yields from such models with postprocessing techniques based on tracer particles; iii) the derivation of synthetic observables from such simulations with three-dimensional (Monte-Carlo based) radiation transfer calculations, including optical spectra, light curves, and also gamma-ray, UV, and polarimetric observables; the direct comparison of the derived observables with astronomical data.

The main goal of core-collapse supernova modelling is to understand the explosion mechanism. While two-dimensional simulations taking into account a sufficient part of the star robustly reached explosion, this seems to be harder to achieve in three dimensions. Such results underline the importance of multidimensional hydrodynamical instabilities together with a detailed treatment of neutrino matter interactions (see Figure 5). Furthermore, the instabilities appearing during the explosive phase may imprint their signature into both the neutrino and gravitational signals whose observation could provide a direct view to the explosion dynamics.

The evolution during the collapse is determined mainly by electron capture in nuclei. The early collapse phase is dominated by iron group nuclei. In recent years, charge-exchange experiments have helped to validate theoretical calculations of this process. The challenge is to extend these experiments to unstable targets. Sensitivity studies have been carried identifying the 500 electron capturing nuclei responsible for the largest absolute change to the electron fraction (and therefore, to the whole core collapse dynamics) up to neutrino trapping. Figure 6 shows that nuclei located around N=50 and N=82 become most important during the last phases of the collapse. They are predicted to be very abundant because of their magicity. But magicity could be quenched away from stability. The nuclear mass of these nuclei is therefore the other key observable to be measured and connects with r-process nucleosynthesis discussed earlier. An improved understanding of electron capture

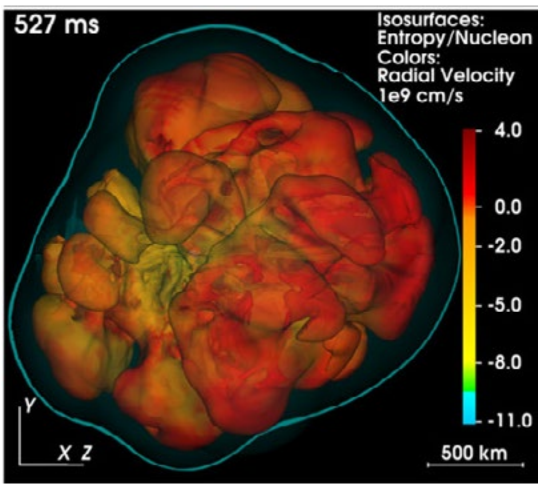


Figure 5: Explosive models of core-collapse supernova in three-dimensions have been developed. They show the important impact of hydrodynamic instabilities and neutrino reactions. [Astrophys. J. 808, L42 (2015)]

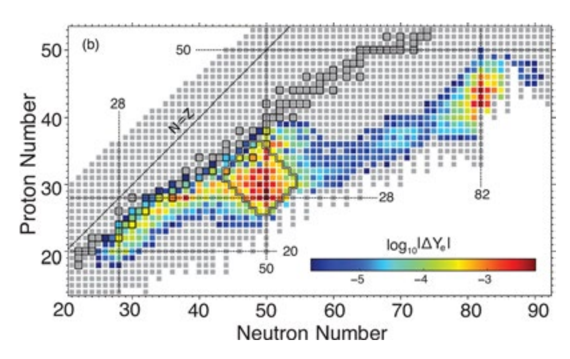


Figure 6: Regions of the nuclear chart with the largest impact on the collapse of massive stars. Many of these regions will become accessible at new radioactive beam facilities [Astrophys. J. 816, 44 (2016)]

and beta-decay is also becoming critical in efforts to understand the dynamics of ONeMg cores both in electron capture supernova and accretion induced collapse.

During the explosive phases of supernovae, neutrino matter interactions are especially important. Fundamental aspects required to understand the multidimensional nature of supernova explosions include neutrino energy transfer and how hydrodynamical instabilities develop. Recent years have seen important advances in the description of these processes. Calculations now consider the full structure of the weak current including weak magnetism corrections. They provide accurate predictions whenever the system can be approximated as uniform nuclear matter. It remains to address the role of nuclear clusters and the role of correlations at high densities.

The main challenges for modelling core-collapse supernovae are therefore: i) improved descriptions of microphysics (e.g weak interaction processes, and the nuclear equation of state) together with their treatment in neutrino transport codes; ii) the emergence of two- and three-dimensional simulations; iii) the systematic study of the impact of different stellar progenitor structures on the explosion phase; iv) detailed calculations of expected nucleosynthesis yields; v) the prediction of neutrino and gravitational wave signals from the explosion models.

Nucleosynthesis in supernovae

Type Ia supernovae are the main sources of iron group elements in the Universe. Per event, about half a solar mass of radioactive ^{56}Ni is produced that decays through ^{56}Co to ^{56}Fe. The exact composition of iron group yields depends sensitively on the conditions under which the thermonuclear burning proceeds, i.e. differences in the assumed progenitor and explosion scenario. In particular, the production of stable Ni is largely determined by the neutronisation of the material, which is in turn determined by the metallicity of the progenitor and electron captures occurring in the ashes of thermonuclear burning. A particularly informative tracer of the thermodynamic conditions is manganese. Its production is sensitive to the explosion scenario with observable consequences for galactic chemical evolution. Manganese abundances in stars and in solar system material can thus constrain the explosion scenario of normal Type Ia supernova, a result that illustrates how detailed nucleosynthesis modelling may help constrain the unknown progenitor systems of these events.

Most nucleosynthesis calculations are currently carried out based on tracer particles passively advected to multidimensional explosion simulations. These reveal the detailed chemical structure of the explosion ejecta, and form the basis of radiative transfer simulations that predict observables from hydrodynamic explosion models. While possible in principle, direct nucleosynthesis modelling seems unnecessarily expensive in terms of the required computational resources. Nonetheless, a few such calculations may serve as a reference for judging the accuracy of the tracer-based method.

In addition to their contribution to iron-group nucleosynthesis, Type Ia supernovae have been considered as sites of the astrophysical p-process, as some explosion scenarios provide favourable conditions. Success depends on the amount of seed-nuclei in the progenitor material, which, in turn, is determined by the (poorly unknown) evolution of the binary system out of which the supernova explosion emerges.

Turning to core-collapse supernovae, these are the major sources of carbon and oxygen in the Universe. In addition, they determine the early iron enrichment of the Galaxy, since the massive star progenitors evolve to explosion much faster than the white dwarf progenitors of thermonuclear supernovae. Consequently, they are fundamental to understanding the metallicity-age relationship. Supernova light curve observations indicate a broad range of explosion energies, i.e. variation in the amount of ejected ^{56}Ni. In addition to canonical supernova explosions that liberate 1 Bethe (10^{44} J) in energy, superluminous (hypernovae) and faint supernova explosions are also observed. This diversity suggests there may be several explosion mechanisms. The canonical explosion energies of 1 Bethe are probably associated to neutrino-driven explosions that produce neutron stars. Other categories may be driven by a different mechanism, likely involving rotation, magnetic fields and the formation of jets. Neutrino-driven supernova explosion simulations are currently at the forefront in astrophysical modelling. The situation is different for magnetorotational supernovae that still require improvements in modelling and microphysics.

The main challenge in core-collapse supernova simulations remains the development of fully self-consistent explosion models. This requires determination of which progenitors explode, and by what mechanism, and the ability to follow the explosion for the times relevant for nucleosynthesis and mixing in the stellar mantel. Given the very different timescales involved, there is no unified description of explosion and nucleosynthesis. Nucleosynthesis studies are therefore based on parametric explosion models calibrated to observations. Recently, it has become possible to develop neutrino driven explosion models, for a broad range of progenitor masses, that predict nucleosynthesis yields and light curves. In some particular cases, multidimensional explosion models have addressed the role of mixing during the explosion, providing the necessary link to supernova remnant observations.

Neutrino interactions are not only fundamental for the explosion but they also determine the nucleosynthesis. Neutrino-matter interactions in the surface layers of the neutron star determine the spectra of the emitted neutrinos and the nucleosynthesis in neutrino driven winds. The neutron richness of the ejecta is directly related to the spectral differences between electron neutrinos and antineutrinos. This in turn is determined by the nuclear symmetry energy at substantiation energies, which, importantly, has recently been determined for a broad range of densities by a combination of theory, observation and experiment. Simulations based on these constraints have provided improved nucleosynthesis predictions. As discussed earlier, they rule out the possibility of a strong r process in neutrino winds, but do allow for the possibility of producing elements around A~100.

Neutrino-nucleus reactions, including those that result in the emission of neutrons, protons and alpha particles, are fundamental to determine the nucleosynthesis in the stellar mantle, and occur before, during and after the supernova shock passage. They contribute to the production of some key nuclear species such as ^{7}Li, ^{11}B, ^{19}F, ^{138}La and ^{180}Ta, and affect the production of long lived radioactive species like ^{26}Al. Neutrino-nucleosynthesis studies have benefited from novel predictions of the emitted neutrino spectra and from improved predictions of neutrino-nucleus cross sections for several key nuclei including ^{4}He, ^{12}C, ^{20}Ne, ^{138}Ba and ^{180}Hf. In several cases the cross sections have been constrained by charge-exchange data.

The detection of neutrinos from our Sun contributed to the discovery of the phenomena of neutrino flavour oscillations. Neutrinos in the Sun are subject to the Mikheyev-Smirnov-Wolfenstein mechanism in which oscillations occur by a combination of vacuum and matter effects, the latter due to neutrino-electron interactions. In the context of core-collapse supernovae, and in the vicinity of the proto-neutron star, the large neutrino fluxes allow for a non-linear coupling between neutrino flavour states. As a result, collective neutrino oscillations may occur in the region of neutrino decoupling and at greater radii. Our understanding of these effects has improved dramatically in recent years, but the impact on supernova dynamics, nucleosynthesis and neutrino detection on Earth is not yet fully understood. Collective neutrino oscillations are expected to be a general feature of astrophysical environments involving high neutrino densities, such as the early universe, core-collapse supernovae and accretion discs.

Stars reborn

Classical novae and x-ray bursts

Many stars end their lives as a white dwarf or a neutron star. These stars have exhausted their fuel, no longer support nuclear fusion and so slowly cool down. However, if the star is part of a binary system, new fuel can be accreted from the companion star, reigniting nuclear fusion and giving the star a new burst of life. Due to the strongly degenerate conditions a thermonuclear runaway may develop in the accreted material. If the dead star is a white dwarf a classical nova occurs, and if it is a neutron star then an x-ray burst is produced.

Novae:

Explosive hydrogen burning proceeds mainly through the hot CNO cycles, on the surface of the white dwarf. If seed material is present, nucleosynthesis up to calcium may occur, in particular with the NeNa cycle and the MgAl cycle. Processed material is ejected into the interstellar medium. Observables include optical & UV spectroscopy, and gamma-ray astronomy and presolar grains, which are of specific interest since they are sensitive to isotopic abundances. To interpret these observations it is crucial to reduce the nuclear uncertainties. Radioisotopes, such as ^{18}F, ^{22}Na and ^{26}Al, are of particular interest due to their predicted abundance and lifetime. Similarly, the measurement of ^{7}Be lines in the near-ultraviolet range may well provide a way of estimating the contribution of novae to the lithium abundance in the Milky Way and in the Universe in its entirety. Observationally, several future instruments are promising for detecting such a unique nova nucleosynthesis signal, e.g. eAstrogam.

Uniquely, of all stellar explosions, almost all the nuclear physics input to nova models is based on experimental data, and this makes them important tests for explosion mechanism models. As explosive hydrogen burning in classical novae involves stable and radioactive nuclei relatively close to the proton-rich side of the valley of stability, experimental studies of these nuclear processes are possible at small-scale stable beam accelerators and at the existing generation of radioactive ion beam facilities. However a few key reactions (e.g.^{18}F$(p,\alpha)^{15}$O, ^{25}Al$(p,\gamma)^{26}$Si, ^{30}P$(p,\gamma)^{31}$S) are still not sufficiently well constrained and remain the target of further experimental attention.

Current state-of-the-art nova modelling relies on 1D, i.e. spherically symmetric, hydrodynamic simulations, and has been capable of successfully reproducing many observational features. However, certain aspects, such as the way the thermonuclear runaway develops and the treatment of convective transport, clearly require a multidimensional approach. To date, 2D and 3D simulations for realistic physical conditions have been restricted to "convection-in-a-box" studies, aimed at characterizing convective transport during the stages prior to mass ejection. The simulations performed rely on the evolution of an accreting white dwarf, initially followed in 1D and subsequently mapped into a 2D or 3D domain as soon as the temperature at the envelope base reaches 100 MK. To reduce the overwhelming computational load, such simulations frequently include a very simplified nuclear reaction network to account exclusively for the energetics of the explosion.

Multi-D simulations reveal good agreement with the gross picture outlined by 1D models, e.g., the critical role played by the β^{+}-unstable nuclei ^{13}N, ^{14,15}O, and ^{17}F in the ejection stage, and consequently, the presence of large amounts of ^{13}C, ^{15}N, and ^{17}O in the ejecta. Some remarkable differences though have also been found, the foremost of which is that the thermonuclear runaway is in fact initiated as a myriad of irregular, localized eruptions at the envelope base caused by convection-driven temperature fluctuations.

Since turbulent diffusion efficiently dissipates any local burning around the core, the runaway eventually spreads along the stellar surface, such that the expansion and progress of the runaway towards the outer envelope becomes almost spherically symmetric. Moreover, the core-envelope interface is found to be convectively unstable, providing a source for metallicity enhancement through Kelvin-Helmholtz instabilities, which can naturally lead to self-enrichment of the accreted envelope with core material, at levels that agree with observations. Pioneering 3D simulations of mixing at the core-envelope interface provide an explanation of the origin of the highly-fragmented, chemically-enriched, inhomogeneous nova shells, observed in high-resolution spectra, interpreted as a relic of the hydrodynamic instabilities that develop during the initial ejection stage.

X-ray bursts:

Type I x-ray bursts are bright and frequent events showing a rapid increase in luminosity due to a thermonuclear runaway on the surface of a neutron star. To understand their light curves, and also the properties of the underlying neutron star, detailed information on nuclei and the nuclear reactions involved in the thermonuclear runaway is needed. Due to the higher temperatures and densities of neutron stars as compared to classical novae, the nuclear flux can break-out from the hot CNO cycle through the $^{15}O(\alpha, \gamma)^{19}Ne$, $^{14}O(\alpha, \gamma)^{17}F$ and $^{18}Ne(\alpha, p)^{21}Na$ reactions. Material is processed to heavier masses by the αp-process and then the rapid proton capture (rp)-process, which lies close to the proton dripline. The pathway may reach masses around A=100, where the flow is expected to terminate with the SnSbTe cycle.

In contrast to classical novae that eject material into the interstellar medium, x-ray bursts are not thought to produce significant ejecta, due to the strong gravitational potential of the neutron star. There is therefore no observational information on the products of nucleosynthesis with which to compare the models. However, the light-curves are closely related to the energy released by (α, p) reactions and, to a lesser extent, (p, γ) reactions, and a comparison with observational data is possible.

Also in contrast to classical novae, most of the nuclear physics input to x-ray burst models is not experimentally determined. Despite significant effort over more than two decades the rates of the breakout reactions are still not sufficiently well known. Masses and lifetimes close to the proton-drip line are needed, and the reaction rates along the αp- and rp-process path are the focus of experiments.

Traditionally, hydrodynamic studies of type I x-ray burst nucleosynthesis have been performed in 1D with truncated nuclear reaction networks. However in the last decade, following fast developments in computational capabilities, several groups have carried out very detailed nucleosynthesis calculations coupling hydrodynamic models and extensive nuclear reaction networks containing around 300 isotopes (or up to 1300 isotopes in the framework of adaptive networks). 1D simulations have proved successful in reproducing the light curve shapes and recurrence periods. The burning front likely propagates subsonically (i.e., a deflagration), and the outburst is likely quenched by fuel consumption rather than by envelope expansion as in novae. The most complex nuclear path is achieved for mixed H/He bursts, which are driven by the 3α-reaction, the αp-process (a sequence of (α, p) and (p, γ) reactions), and the rp-process.

Some important issues remain to be clarified. One is whether type I x-ray bursts may indeed be capable of contributing to Galactic abundances. The second is the link between type I x-ray bursts and the production of very energetic superbursts. Indeed, the duration and energetics of superbursts suggest that fuel ignites at deeper layers than in normal type I bursts, at densities typically exceeding 10^9 g cm^{-3}, close to the neutron star crust. Since neither hydrogen nor helium likely survive at these depths, it has been suggested that superbursts may be powered by ignition of carbon-rich fuel. But controversy remains as to how much carbon is actually consumed during a type I burst, and whether enough carbon is leftover to power a superburst, a possibility not favoured by current models. Alternative models rely on combined stable and unstable burning regimes of the accreted H/He mixture, but the scenario requires further analysis.

To date, no self-consistent 3D simulation of an burst, for realistic conditions, has been performed. A number of efforts have focused on the analysis of flame propagation in the accreted envelopes, or on "convection-in-a-box" studies that characterise convective transport during the stages prior to ignition. A number of multidimensional studies of detonation flames on neutron stars have been performed but these impose physical conditions that bear little resemblance with those expected during x-ray bursts.

Matter at extreme conditions: neutron stars

To understand the physics of neutron stars and binary mergers, it is important to constrain the equation of state (EoS) of neutron-rich strongly interacting matter. Although the EoS of symmetric nuclear matter has been constrained over a range of densities around the saturation density, the spread of values at high densities still remains large. The knowledge of *asymmetric* nuclear matter is very limited, mainly because of difficulties in determining accurately the symmetry energy.

Recently, a variety of experimental methods have studied the symmetry energy, and its slope parameter, in detail. The slope parameter provides the dominant baryonic contribution to the pressure in neutron stars and affects the neutron skin thickness. The latter can be extracted from experiments studying the parity violation in electron scattering or coherent pion photoproduction. Further relevant nuclear phenomena that have recently been extensively studied include various collective excitations, e.g., isovector giant dipole and quadrupole resonances, pygmy dipole transitions, Gamow-Teller resonances, anti-analogue giant dipole resonances, etc.

Many-body calculations based on ab initio or nuclear energy density functional methods, that describe the properties of finite nuclei, represent the key theoretical approaches for the description of the EoS. In the framework of nuclear density functional theory, successful techniques have recently been developed and exploited in connecting the experimental data with the density dependence of the symmetry energy. Ab initio approaches based on chiral effective field theory have been used to determine the EoS of uniform neutron matter up to saturation density, including contributions of two and three body forces. These calculations also provide an important consistency check of how well realistic interactions, which have been adjusted to scattering and few body data, can be applied to describe homogeneous systems like neutron matter. Techniques to connect ab initio approaches for the low density regime with density functional approaches at the high density regime are also being developed.

Another promising approach is based on statistical methods associated to the covariance analysis of observables, which allows mapping of the properties that govern the EoS to those characterising static and dynamic phenomena in finite nuclei. In particular, the isovector excitations in nuclei provide additional constraints for the neutron star core-to-crust transition density and pressure. The dipole polarisability, associated to the isovector dipole excitations in nuclei, has been established as a promising constraint for the neutron skin thickness and the symmetry energy.

The incompressibility of symmetric nuclear matter (a measure of the curvature of the equation of state at saturation density) represents another relevant quantity. While it can be determined from the compression modes of collective nuclear vibrations, the model dependent connection between experimental data and the nuclear matter incompressibility result in large uncertainties in the extracted value.

Presently, the main astrophysical constraint for the EoS stems from observations of two binary systems. In both, a very massive neutron star is partnered by a white dwarf. The masses of these two neutron stars have been measured precisely to be around two solar masses. This result severely constrains the stiffness of the EoS at high densities and already excludes many models (see Figure 7). A yet better constraint on the EoS would be a determination of both radius and mass of the same object. For low-mass neutron stars this could be translated into a constraint for a particular combination of the incompressibility and slope of the symmetry energy.

The composition of matter at the suprasaturation densities reached in neutron star cores is very uncertain. Particles other than nucleons and electrons are expected to appear. Muons, pions, kaons and their condensates, hyperons, nuclear resonances and quarks have been considered. There is even the possibility of absolutely stable strange quark matter and pure strange stars. The constraint arising from the observation of two solar mass neutron stars has triggered intensive discussions about the neutron star interior. The appearance of additional degrees of freedom tends to soften the EoS and lower the maximum mass but large uncertainties remain due to the poorly understood interaction in the medium. Phenomenological hadronic and quark models

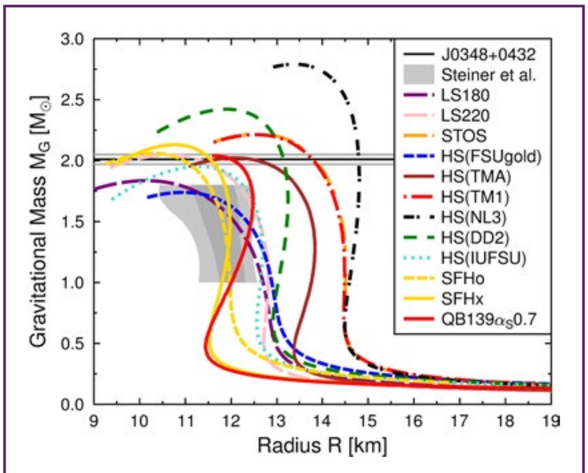


Figure 7: Current constrains on the mass and radius of neutron stars (grey region) compared with predictions of different equations of state (lines) [Eur. Phys. J. A 50, 46 (2014)]

can easily be supplemented with the necessary repulsion at high densities so that maximum masses above two solar masses can be obtained. Hyperonic degrees of freedom, which are expected to appear at about twice the saturation density, are difficult to reconcile with a two solar mass neutron star. Addressing this "hyperon puzzle" requires additional repulsion to stiffen the high-density EoS. Hyperonic and three-body interactions have been extensively studied in this respect. However, experimental data are scarce and furnish only weak constraints on the interactions.

There exist many EoSs for cold neutron star matter, and to a lesser extent, for homogeneous hot matter in proto-neutron stars. To be usable in astrophysical simulations, the EoS has to encompass a wide range of densities, temperatures and isospin asymmetries. Such "general purpose" EoSs are rare; there exist only about 40. These must also include a description of clusterised and/or inhomogeneous matter at subsaturation densities. Such general purpose EoSs though are of great importance for astrophysics, as they can be used in simulations of neutron star mergers or core-collapse supernovae.

As a sub-class of general purpose EoSs, unified EoSs for cold neutron stars are those that describe matter from the surface to the centre of the neutron star in a unified manner, i.e., on the basis of the same interaction model, including a description of inhomogeneous matter in the crust. This is important for detailed predictions of neutron star radii and for dynamical properties.

All available general purpose EoSs are based on phenomenological approaches. Even at this level, several of them are clearly ruled out by experimental or astrophysical observations and no presently existing model is consistent with all available constraints.

ASTRONOMICAL OBSERVATIONS

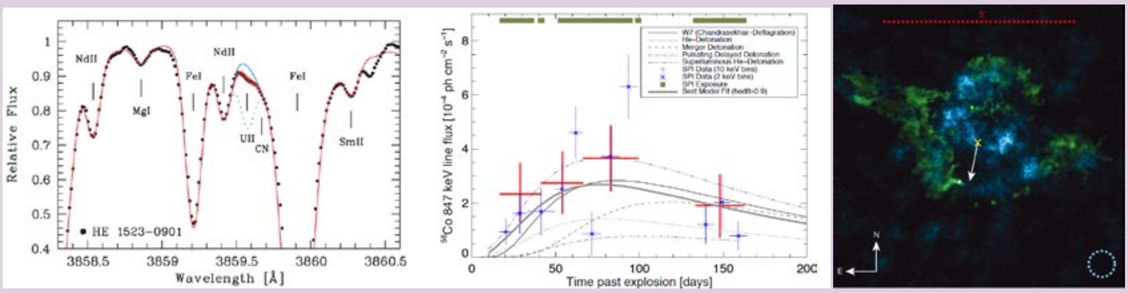
Observations of characteristic lines in stellar spectra have been the backbone of determining elemental abundances in stars. The isotopic composition of winds and ejecta, and their kinetic and radiative feedback, makes stars the key agents that drive the evolution of galaxies. The imprints of nucleosynthesis may be observed in various ways: the photospheres of single stars; characteristic lines from interstellar gas; collective spectra of entire populations of stars or galaxies; and dust grains collected in meteorites. Understanding how characteristic spectral features arise is key to interpretations of astronomical spectra. Often, many sources contribute and are superimposed, with decomposition challenging due to the complex, non-linear and often stochastic processes, thus making it very difficult to relate observational abundance data directly to nuclear reactions in cosmic objects. Instead, models of stars and explosions are combined with ejecta propagation, and with the frequency of their occurrences, to construct sophisticated galactic chemical evolution models. These serve as tools to validate the underlying physics assumptions against astronomical observations. Simplifying assumptions are often required, such as instantaneous recycling of matter between stellar generations, or assumption of spherical symmetry in explosions, but advances in our theory, methods and computing power continue to drive progress. Identifications of a wide variety of metal-poor stars have founded a field now called Galactic Archaeology, as metal content reflects stellar age, and thus the history of enrichment of Galactic matter with different elements may be studied. In recent years, large photometric and spectroscopic surveys have been conducted, providing spectra for millions of stars in our Galaxy, and thousands of metal poor star spectra. From this, different populations of stars in our Galaxy have been recognised, i.e. the different enrichment histories tell us if stars were born in unusual environments, if they reflect what we expect from the ten-gigayear evolutionary history of stars in our own Galaxy, or if they may have been formed from material originally outside our Galaxy that has merged with the Milky Way Galaxy. The detection of uranium is a recent achievement that allows dating independently of cosmological model assumptions, and improved constraints on pollution from r-process ejecta. With Gaia and Kepler, it is now possible to add precision to secondary parameters that are key to such study, namely the distance to the sources of stellar photosphere spectra, and the age of the parent star. Even larger spectroscopic surveys based on high-multiplex spectrographs are underway to complement the Gaia information with detailed chemistry and radial velocities (e.g. WEAVE and 4MOST).

Beyond stellar spectra, several 'new astronomies' have arisen since the advent of radio astronomy in the 1930s. Some of these are sufficiently matured to also use them in the study of evolving cosmic matter composition. Most importantly, meteorites provide us with material from the history of our solar system, which can be analysed for its isotopic composition in terrestrial laboratories. The isotopic composition of the Sun thus has been established, complementing spectroscopy of the sunlight. Within those meteorites, inclusions

Box 2: Astronomical observations versus astrophysical models

Measured elemental abundances have been the foundation of nuclear astrophysics. One of the recent findings was the detection of uranium with ESO's Very Large Telescope (left). More precise data are now becoming available for a vast number of stars in our Galaxy, thanks to ESA's Gaia space satellite instrumentation, and new and planed multi-object spectrographs such as WEAVE and 4MOST. These enable discrimination of abundance pattern systematics for stars of different origins and ages, "Galactic archaeology", and the test of modern descriptions of chemical evolution of cosmic gas in and between galaxies.

Multi-messenger data complement the astronomical observations. Meteorites and stardust embedded therein have been essential for determining isotopic ratios from solar system material, and also tracing dust from AGB star, novae and supernovae nucleosynthesis sources. Astronomical observations at other wavelengths, from radio and sub-mm molecules to x- and gamma-ray nuclear lines also carry isotopic information. X- and gamma-ray space observatories allow measurements directly at individual nucleosynthesis sources. Gamma-rays from the ^{56}Ni decay chain have been discovered for the first time from a supernova of Ia-type (centre). The Cassiopeia A supernova remnant, at only 3.4 kpc distance, has allowed direct imaging of ejected nucleosynthesis products: the image of the ^{44}Ti spatial distribution within the remnant is a recent breakthrough (right). ^{44}Ti is especially important as it is expected to be produced near to the boundary between the material falling back onto the collapsing core and that ejected into the surrounding medium, and thus its observation probes the explosion mechanism. Moreover, its spatial distribution directly probes explosion asymmetries. Key nuclear reactions, including ^{44}Ti*(α, p)*, determining the production are being studied in several European labs.



of extrasolar material was recognised about 40 years ago, and has been associated with stardust from stars, novae, and supernovae outside our solar system. The isotopic composition measured in such stardust grains has led to important constraints on nuclear reactions, in particular for AGB stars, and more recently, also for supernovae.

Radio astronomy has matured and is now capable of both spatial and spectral measurement of molecules and their isotopic variants, even in distant galaxies. Although the variety of species observed leaves a task of species identification, and chemistry in interstellar space is required to interpret such data, new constraints on cosmic nucleosynthesis arise from measurements with, e.g., SOFIA, ALMA and IRAM.

At higher electromagnetic energies, x-ray and gamma-ray telescopes have added spectroscopy of hot plasma. Since nucleosynthesis sources, and in particularly supernovae, are very energetic and eject nucleosynthesis ashes in the form of hot plasma, this allows the study of sources of nucleosynthesis directly. Recent progress here involves, e.g., constraints on the morphology of nucleosynthesis ejecta in the Cassiopeia A supernova remnant. Chandra satellite measurements had shown that in different atomic recombination lines the structure of the remnants appears different, with surprises from iron appearing outside regions of silicon emission. NuSTAR imaging of the same remnant in ^{44}Ti radioactivity measured at ~70 keV then showed highly inhomogeneous emission, surprising in that it shows the non-sphericity of a supernova even from messengers of its innermost regions. On the other hand, a qualitative similarity to recent 3-dimensional simulations is encouraging, confirming that instabilities of the inner burning regions are at the origin of the observed clumping. A second example is the direct proof that ^{56}Ni radioactivity powers supernova light, from INTEGRAL/SPI observations of the gamma-ray lines characterising the ^{56}Ni radioactive decay chain through ^{56}Co lines leaking out after several weeks. With detailed observations of diffuse nucleosynthesis in ^{26}Al gamma-rays, a new and independent window has been opened to assess massive star feedback and cosmic matter recycling, making use of a radioactive clock with a million year characteristic decay time. ^{60}Fe gamma rays have also been seen, yet instrument sensitivities are insufficient to similarly exploit these much fainter signals in constraining the s-process in massive star shell burning.

Finally, the detection of the first gravitational wave events, even though from different objects, show that this astronomical window is now also ready to witness neutron star mergers or a nearby core-collapse supernova in our Galaxy. Constraints on the explosion dynamics, and on the formation of a neutron star and its equation of state are among the prospects of such a measurement.

REQUIREMENTS FOR NUCLEAR EXPERIMENT, AND THEORY

Experimental opportunities

Accelerator facilities

Radioactive beam facilities

New facilities in Europe, such as FAIR/GSI, SPIRAL2 at GANIL, HIE-ISOLDE at CERN, SPES-INFN and ELI IGISOL at ELI-NP, will provide unprecedented opportunities to study exotic nuclei of interest for nuclear astrophysics. In particular, major steps on the production of nuclei of interest for the rp-, i- and r-processes will be realised. This breakthrough, coupled to the next-generation detector systems and the new experimental techniques, will allow more precise and new experimental measurements of nuclear inputs relevant for astrophysical models, particularly for supernovae, mergers and x-ray bursts. Moreover, the study of nuclear properties and reactions far from stability will provide much needed experimental data to test and constrain the nuclear models, which still provide the majority of nuclear input to explosion models.

In the immediate future, rp-process nuclei can be explored e.g. employing beams from SPIRAL1 and new facilities, such as S3 at GANIL and MARA at JYFL. In the lower-mass region, reaction studies in inverse kinematics employing intense radioactive beams will increase our knowledge of reaction rates needed for the astrophysical reaction network calculations. Surrogate *(d, n)* proton-transfer reactions have shown to be promising candidates for determining the relevant states and resonance strengths for *(p, γ)* reactions. In combination with the state-of-the-art detectors, such as the high-resolution gamma-ray detector AGATA, these will lead to a significant improvement in the knowledge of key reactions for the rp-process. Direct reaction studies as well as Coulomb dissociation reactions performed at the R3B facility at FAIR (GSI) are also essential for the rp-process. New kinds of experiments become available at the storage rings at FAIR. The first proof-of-principle experiments have already been performed for nuclear astrophysics at ESR storage ring at GSI.

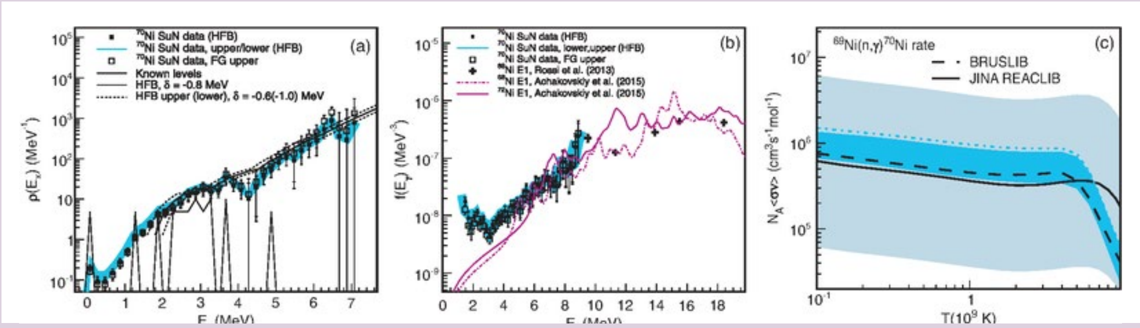
The masses of the involved nuclei determine the path of the rp-process and have a strong effect on the x-ray burst light curves and final abundances. Penning-traps have revolutionised the possibilities of high-precision mass measurements of radioactive isotopes. New techniques, employing phase imaging or Fourier-transform ion cyclotron resonance mass spectrometry, make it possible to do measurements faster or with lower yields than ever before. Penning traps at future RIB facilities, such as MATS at NUSTAR/FAIR and MLLTRAP (coupled to PIPERADE in some cases) at SPIRAL2 will provide new opportunities and complement/support the work done at the existing ISOLTRAP, SHIPTRAP and JYFLTRAP facilities. Multi-reflection time-of-flight mass spectrometers (MR-TOF) have shown to be efficient, yet not so precise, tools for mass measurements of shorter-lived nuclei. New MR-TOF mass spectrometers are planned for most new facilities, such as for the low-energy branches of MARA at JYFL and S3 at SPIRAL2

Beta-decay properties of nuclei along the rp-process path are also necessary input to x-ray burst models. Here, both Penning traps and MR-TOF devices provide isotopically or even isomerically pure beams for decay spectroscopy experiments. As low-energy isomers can be thermally excited at the peak temperature of the bursts, isomeric states can play a critical role in x-ray busts, making their identification and study relevant for the modelling of the rp-process. Beta-delayed particle decays have yielded much information on the resonance strengths and states in the lower mass region. New active target time projection chamber detectors, such as ACTAR, will help in detecting lower proton energies than previously possible, often a critical requirement for astrophysics studies. Total Absorption Spectrometers will yield better understanding of the Gamow-Teller strength distribution and electron-capture decay probabilities. Furthermore, complementary studies employing charge-exchange reactions will enable detailed comparisons of the Gamow teller strengths.

For the production of heavy elements occurring in supernovae and mergers, the European ISOL

Box 3: Experimental constraints on astrophysical reactions involving exotic nuclei

One of the major challenges in modeling nucleosynthesis in explosive environments is the fact that the nuclear properties of the many nuclei involved are not known experimentally. This is particularly the case for the r-process that requires neutron captures and beta-decay rates for neutron-rich nuclei. Beta-decay experimental data for r-process nuclei has dramatically improved theoretical calculations. The situation is different for neutron capture rates although recent experimental developments offer the possibility of constraining such rates far from stability.



Phys. Rev. Lett. 116, 242502 (2016)

facilities HIE-ISOLDE, SPES and SPIRAL2, will soon provide more intense beams of some nuclei located along the r-process path (fission products of uranium). In the future, a major step will be made with the FAIR-NUSTAR facility, which is expected to give access, for the first time, to many of the r-process path nuclei at N=126 by means of fragmentation of a high-intensity and high-energy ^{238}U-beam. Thus, a change of paradigm may be expected in the near future, providing first experimental data in a yet unknown region of the nuclear chart, and very stringent constraints for the r-process nucleosynthesis of the heaviest stable nuclei.

Recent developments at LNL and GANIL have demonstrated the suitability of multi-nucleon transfer reactions to produce large yields of N=126 nuclei. This very promising method will offer new opportunities. In particular, the low neutron binding energy of neutron-rich species can be used to produce extremely neutron rich target-like fragments. Transfer reactions on a lead target using e.g. high intensity ^{94}Rb beams feasible at HIE ISOLDE or SPES can be used to produce very neutron-rich heavy nuclei around the N=126 region. Fragmentation and nucleon transfer are rather complementary production mechanisms, and one can expect first-hand access to many of the r-process nuclei directly at N=126 as well as to those involved in the freeze-out phase. Advanced instrumentation capable of coping with the severe background conditions is being developed and tested in existing facilities such as ALTO, GANIL, GSI, or LNL in Europe and abroad at NSCL (USA) and RIKEN (Japan). These advanced detection systems with high sensitivity and selectivity will allow one to experimentally determine masses, beta-decay half-lives and beta-delayed neutron-emission of the most exotic neutron-rich nuclei. It is worth mentioning that almost all the nuclei to be discovered are expected to be beta-delayed neutron emitters, a process that has a two-fold impact in final r-process abundances, as on one side it shifts the mass-distribution towards lower values, and on the other it may induce a reactivation of the r-process in its later stages. Sensitive neutron counters as BELEN at FAIR will allow measurements of delayed neutron emission for the most exotic nuclei.

Apart from the ground state and decay properties, one of the ingredients influencing the final r-process abundance pattern is the neutron capture reaction rates on the neutron-rich unstable nuclei involved. Stellar neutron capture reaction rates are also of relevance for the recently proposed i-process mechanism of nucleosynthesis. These cross-sections cannot be directly measured and thus indirect approaches are needed. A leap forward may be expected in the near future due to on-going development of several complementary approaches. One such is based on detailed study of the electric dipole response of exotic nuclei, wherein high energy-resolution is provided over a broad energy spectrum to enable identification of the low-energy gamma-ray strength distribution, i.e. the so-called Pygmy resonances. Measurements of the Pygmy resonance in stable and unstable nuclei have been found to represent a rather large influence on the neutron capture stellar rates and, correspondingly, on the final r-process abundance pattern. Advanced detection systems such as AGATA and R3B-LAND at NUSTAR will allow the mapping of the electric dipole nuclear response on very neutron-rich nuclei, and using it to infer more realistic neutron capture cross sections.

Other approaches, still under development, employ transfer reactions as surrogates for neutron capture. Two different innovative techniques are being developed in this field. One of them induces transfer reactions employing radioactive ion beams in inverse kinematics, exploiting the high beam energy resolution, high luminosity and target purity attainable in storage rings like ESR/CRYRING at FAIR-NUSTAR. Present studies have shown the feasibility of surrogate methods for determining fission cross sections, whereas a successful methodology for radiative neutron capture has yet to be developed and validated.

Other techniques intend to exploit the high intensities of secondary beams provided by the SPES facility, in combination with high-resolution measurements afforded by high-granularity particle and gamma-ray tracking detectors. This methodology could help to constrain the s-wave component of neutron capture, which is in most cases one of the main contributions to the overall stellar neutron capture rate.

Finally, Total Absorption Spectroscopy beta-decay measurements, which are sensitive to the γ-ray strength distribution beyond the neutron separation threshold of the daughter nucleus, in combination with high-resolution neutron-spectroscopy measurements, using new time-of-flight spectrometers, like MONSTER, can also help to experimentally constrain the neutron capture rates in the relevant stellar energy range.

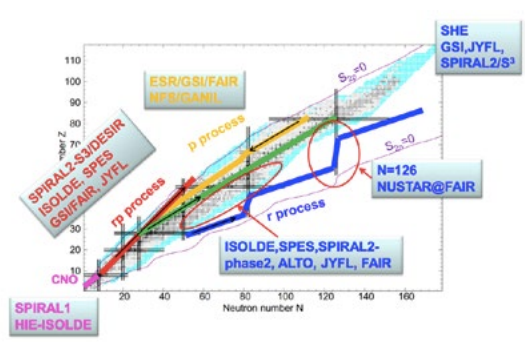


Figure 8: European radioactive beam facilities offer unprecedented and complementary capabilities to study exotic relevant for the evolution and nucleosynthesis in explosive environments

In the next 5-10 years, with several new RIB facilities operational in Europe, one can expect a remarkable push to broaden knowledge of the nuclear chart, particularly in the heavy mass region, delivering a wealth of new data (masses, half-lives, neutron branchings, reaction cross sections) that will be direct input for r-process model calculations. A wide assembly of detection systems and even new techniques are being developed and tested at existing facilities in order to get as much and accurate information as possible, once the new RIBs become accessible.

Underground nuclear astrophysics

The LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration celebrating its 25th anniversary in 2016 has shown the tremendous advantages of a deep underground location for an accelerator in experimental nuclear astrophysics. Indeed, the extremely low radiological background has allowed, for the first time, nuclear physics experiments with count rates down to a couple of events per month. Consequently, important reactions responsible for the hydrogen burning in the Sun have been studied down to the relevant stellar energies. Although LUNA is still the only deep underground accelerator facility, several new similar projects are planned or under construction around the world. To keep the world-leading role of Europe in this area and compete successfully with Chinese or US initiatives, the future European underground accelerator facilities must receive strong support.

The next phase of the LUNA collaboration, mainly devoted to helium and carbon burning, is already in preparation.

The so-called LUNA-MV project will employ new high-current single-ended 3.5 MV accelerator delivering hydrogen, helium and carbon (also double ionized) beams. With its energy range and beam intensity, an ambitious list of key reactions of nuclear astrophysics are to be tackled, including the neutron source reactions of the s-process ($^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$), the "Holy Grail" of nuclear astrophysics ($^{12}C(\alpha,\gamma)^{16}O$), ^{12}C+^{12}C fusion, and several hydrogen and alpha burning reactions.

An underground accelerator is also proposed at the Canfranc underground laboratory in Spain. The planned CUNA (Canfranc Underground Nuclear Astrophysics) project aims first at the measurement of the neutron source reactions of the s-process ($^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$). Similarly, a 5 MV pelletron accelerator is under installation in the shallow underground laboratory "Felsenkeller" in Dresden, Germany. The accelerator will serve as an open user facility and studies of the reactions of the H, He and C burning processes are planned.

Stable beam accelerator facilities

The very fact that stellar temperatures correspond to extremely low energies means that in many cases important reactions can be studied at small accelerators providing low-energy beams. Such accelerators are often found at small-scale facilities that have therefore been one of the main driving forces in experimental nuclear astrophysics over the years.

Such facilities maintain their relevance. For example, when direct measurements of astrophysical cross-sections close to or in the Gamow peak are not achievable, indirect methods can be used advantageously. For physics cases involving nuclei only a few units from the valley of stability, such indirect studies can be performed at small-scale facilities operating stable beams. In this context it is important to highlight the need to preserve electrostatic machines like tandem Van de Graaff accelerators from possible shut-downs in the near future. Prime examples of such machines are at INFN-LNS, INFN-LNL, IPN Orsay and MLL Munich. Magnetic spectrometers (Enge Split-pole and Q3D) are the instrumentation of choice to perform high-resolution spectroscopic studies that determine the parameters of key nuclear excited states. Europe currently maintains a high profile in these studies but, with several magnetic spectrometers coming online in the U.S. in the next five years, it is crucial that European facilities support and invest in these instruments.

Although most of the reactions in quiescent burning processes of stars have already been studied experimentally, the rates of these reactions are not yet known with the high precision now required by improved astrophysical models and observations. The fast progress of astronomical observation techniques triggers the continuous improvement of stellar models. The sophisticated stellar models, therefore, require new high precision nuclear physics input. Higher intensity ion sources and accelerators, or improved-quality targets are certainly needed. Studying a reaction with complementary methods such as in-beam gamma-detection, activation, accelerator mass spectrometry or various indirect methods like Trojan Horse or the use of asymptotic normalisation coefficients, can significantly increase the precision and reliability of data. Measuring the cross section of a reaction in a wide energy range may aid the theory-based extrapolation of the data to low energies.

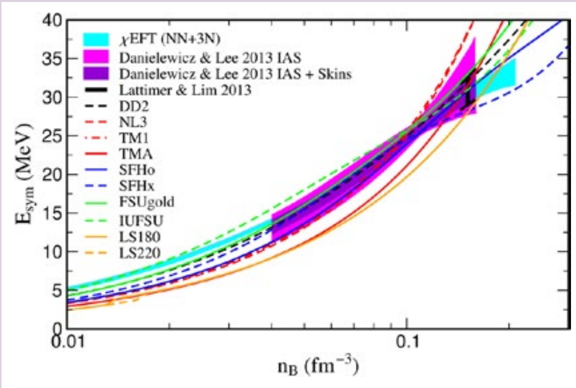
Accelerator mass spectrometry (AMS) is a tool to measure long-lived radionuclides at extremely low concentrations. This technique has been used for nuclear astrophysics research primarily in two ways. Firstly, in dedicated experiments where a low cross-section nuclear reaction for the production of a radionuclide is studied, AMS is able to detect small numbers of produced atoms of the radionuclide in the target material after the reaction process. These measurements complement techniques that detect prompt reaction products (e.g. at the n_TOF facility) or the measurements of shorter-lived radionuclides via decay measurement after the irradiation (activation measurements). The technique is useful for long-lived nuclides that are difficult or impossible to detect via decay measurements, e.g. ^{41}Ca with a half-life of about 10^5 years, is virtually impossible to detect otherwise. Mainly s-process reactions have been studied with irradiations at neutron facilities preceding the AMS measurement, but also some charged particle reactions (e.g. ^{25}Mg(p,γ)^{26}Al).

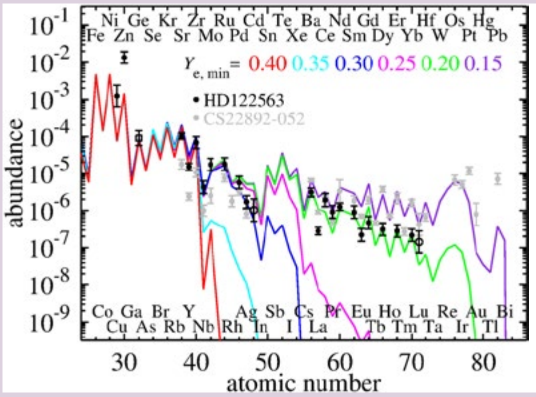
Secondly, the superb sensitivity of AMS may be used to detect traces of recent nucleosynthesis events. Some long-lived nuclides have no significant sources in our Solar System and on Earth, but are produced in significant quantities during nucleosynthesis and are emitted into the interstellar space during supernova explosions. ^{60}Fe (halflife of 1.3 My) and ^{244}Pu (81 My) are two candidates. The finding of a clear signal from 2-3 million years ago in a deep-sea FeMn crust points to a direct deposition of recently produced ^{60}Fe from a nearby supernova and complements space-based observation of ^{60}Fe by γ-ray astronomy. The measured abundance of the r-process nuclide ^{244}Pu (in total only 5 atoms were detected) is about two orders of magnitude below the value expected from continuous production in our Galaxy. This information adds a piece to the puzzle of the possible site(s) of the r-process. The measured low ^{244}Pu abundance might be the result of rare but high-yield event that produced the heaviest elements (actinides), in contrast to supernovae that are likely to be responsible for the main r-process nuclides.

AMS is generally based on electrostatic tandem accelerators that provide the elimination of molecular interference in the mass spectrometric analysis. For identification of the rare radionuclide in the presence of intense isobaric interference (e.g. ^{60}Fe with interference of stable ^{60}Ni), rather high ion energies are required (terminal voltages above 10 MV). In Europe there is currently only the accelerator facility in Garching of the Technical University in Munich that can perform such challenging measurements. It is important for the field that at least one large tandem accelerator facility is capable of doing AMS at high energies; many other long-lived nuclides that do not require the identification within the isobaric background, can be done with less effort and higher precision

Box 4: Heavy element nucleosynthesis in core-collapse supernova

The determination of the heavy elements produced in core-collapse supernova requires accurate predictions for the spectral differences between electron neutrinos and antineutrinos. These differences are related to the nuclear symmetry energy at sub saturation densities. A combination of nuclear experiments and theory and astronomical observations have greatly constrained the density dependence of the symmetry energy. This puts strong constraints on equations of state used in core-collapse supernova simulations and furthers aids determination of the neutron richness, , of the ejected material. This is the main parameter affecting the nucleosynthesis in the ejected material.





and efficiency at smaller accelerator facilities (e.g. at the 500 kV TANDY at ETH Zurich or the 3 MV VERA facility in Vienna).

Neutron beam facilities

Neutron production via (p, n) reactions at low-energy electrostatic accelerators was the initial source of information on stellar cross sections. Fast pulsed electrostatic accelerators are important because they are complementary to white neutron sources due to a combination of unique features, i.e. the possibility to tailor the neutron spectrum, low backgrounds and competitive flux at sufficient TOF resolution. Neutron spectra can be restricted to the immediate region of interest for s-process applications by the proper choice of the proton energy and the thickness of the neutron production target.

The most commonly used (p, n) source is the $^{7}Li(p,n)^{7}Be$ reaction in which neutrons in the energy range from a few to 220 keV are produced by bombarding thin layers of metallic Li or LiF. With proton beams 30 and 100 keV above the reaction threshold at 1881 keV, continuous neutron spectra with maximum energies of 100 and 225 keV, respectively, are obtained, where the first choice offers a significantly better signal to the background ratio at lower neutron energies. The neutron production target consists only of a thin Li layer on a comparably thin backing without any moderator, thus allowing for very short flight paths down to a few centimetres. Examples of such setups include the Van-de-Graaff accelerator at JRC, Geel, Belgium and the 3 MV Tandem Pelletron at CNA, Sevilla, Spain, in the framework of the HISPANOS facility. Recent developments target increased intensity proton beams using RFQ-type LINACS, such as at SARAF (Soreq, Israel) with a liquid lithium target, LENOS (INFN Legnaro, Italy) or FRANZ (Goethe University Frankfurt, Frankfurt, Germany). Future approaches might include inverse kinematics in the neutron production, such as using a lithium beam on a hydrogen target (LICORNE, Orsay, France) or even inverse kinematics during the experiment (ion beam on a neutron target).

The highest neutron yields are obtained in spallation reactions of high-energy beams. As spallation neutrons are very energetic, a moderator near the neutron production target is needed to shift the spectrum to the lower neutron energies of astrophysical interest. The only TOF facility at spallation neutron sources presently operating in Europe is n_TOF at CERN. Here, intense 20 GeV pulses of 7×10^{12} protons produce about 2×10^{15} neutrons per pulse in a massive lead target, corresponding to 300 neutrons per incident proton. The target is cooled with water, which acts also as a moderator. The resulting neutron spectrum ranges from thermal energies of 25 keV to a few GeV. Two flight paths of 20 m and 185 m, together with a proton pulse width of 7 ns, offer excellent energy resolution.

Electron accelerators have been used for neutron production via bremsstrahlung-induced (γ,f) and (γ,n) reactions by irradiation of high-Z targets with pulsed electron beams. GELINA at Geel/Belgium is the only electron-driven, moderated facility for neutron studies in the energy regime of the s-process. The accelerator delivers a 140 MeV electron beam with a pulse width of 1 ns onto a rotating uranium target, and the water-moderated neutron spectra from 25 keV up to 20 MeV can be accessed at 10 flight paths from 10 to 400 m.

At the ELBE accelerator in Dresden-Rossendorf, a 40 MeV electron beam on an unmoderated liquid metal target is used to operate a very compact neutron source characterized by a remarkably high TOF resolution. Applications in astrophysics are hampered, however, by the hard neutron spectrum that is concentrated in the energy range from 0.2 to 10 MeV with an intensity maximum around 1 MeV, too high for most astrophysical (n, γ) measurements.

High resolution γ-beams

The availability of high-brilliance narrow-bandwidth gamma beams, such as the beams that will be available at ELI-NP, will provide new opportunities for photonuclear reaction studies with high resolution. One flagship study is that of the important $^{12}C(\alpha,\gamma)^{16}O$ reaction. Understanding and modelling the evolution and explosion of massive stars requires a 10% uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section at helium burning energies around 300 keV. Due to the extremely small cross section at such low energies, the $^{12}C(\alpha,\gamma)$ reaction has been studied experimentally only down to energies around 1 MeV. The detailed measurement of the reaction cross section and angular distributions for the inverse photodisintegration reaction, $^{16}O(\gamma,\alpha)^{12}C$, is one of the high priority experiments at ELI-NP. An advantages of measuring the photo-dissociation of ^{16}O is a gain in cross section due to detailed balance. The measurement of cross section and angular distributions with precision better than 3% at higher energies, all the way to 14 MeV excitation energy reduce the uncertainty of cross-section extrapolations.

Laser driven reactions

A major challenge in experimental nuclear astrophysics is the direct reproduction of the astrophysical conditions in the laboratory, accessing the finite temperature and screening corrections of the stellar plasma. Experimental studies of nuclear reactions in controlled plasma conditions are becoming possible with the availability of high-power lasers. The new technique of radiation pressure acceleration (RPA), promising production of accelerated bunches at solid-state density, is predicted at the laser intensities achievable at ELI-NP. One proposed exploitation of these high-density accelerated ions is to fission heavy nuclei and induce the fusion of the light fission fragments, thus producing unstable neutron-rich nuclei in the region of the N ~ 126 r-process waiting point.

Nuclear astrophysics with indirect techniques

Indirect methods, such as Coulomb dissociation, asymptotic normalization coefficients, and the Trojan Horse method, have been introduced as alternative approaches for determining cross sections of astrophysical interest. They make use of indirect reaction mechanisms, such as transfer processes (stripping and pick-up) and quasi-free (knock-out) reactions. It is essential to factorise the cross section into a contribution that can be calculated from theory and a quantity that is related to the cross section of the astrophysically relevant reaction. This exploits the fact that peripheral processes dominate the reaction mechanism, where only the asymptotic part of the wave function is relevant. Recently, the capabilities of the Trojan Horse method have been exploited with radioactive beams. Moreover, indirect methods are unique tools to investigate neutron captures on very short-lived radioactive nuclei, such as $^{26}Al^*(n,p)$ and $^{26}Al^*(n,\alpha)$, involving the isomeric state of ^{26}Al and not accessible via direct measurements.

Developments in nuclear theory

The present status of general purpose EoSs at finite temperature and various densities and asymmetries is not satisfactory. There is still need for new general purpose EoSs, which employ modern energy-density functionals (or even beyond) with good nuclear matter properties, that include additional degrees of freedom at high densities and temperatures, and that give a detailed description of clustering at subsaturation densities. Due to the computational and conceptual complexity of more microscopic methods, all available general purpose EoSs are based on phenomenological approaches.

Especially for neutron stars, there is also a need for new unified EoSs, especially if accurate radius measurements will become available in the future. Besides thermodynamic quantities, it would be advantageous to include pairing in a self-consistent description, e.g., relevant for neutron star glitches and cooling. In addition, the transport properties should be calculated consistently with the EoS model. Regarding high densities, the predominant degrees of freedom should be identified and better constrained by forthcoming astrophysical observations, constraints from experiments, and robust theoretical studies. If phase transitions are considered, e.g., to quark matter, it is important to treat them correctly, especially if multiple conserved charges are involved. At best, Coulomb and surface energies should be taken into account explicitly leading to finite-size structures and Pasta phases when one reaches the regime where matter is "frustrated".

Recent years have seen tremendous progress in ab initio approaches for nuclear structure calculations and descriptions of nuclear matter, particularly neutron matter. Many-body techniques have been applied up to medium mass nuclei and for selected heavy nuclei. Applications for Big Bang Nucleosynthesis and hydrogen burning reactions have already taken place and further progress for intermediate mass nuclei is expected particularly involving alpha induced reactions. Determination of the highest densities that ab-initio approaches can reliably describe is needed, so as to put constraints on the EoS of uniform matter at all relevant isospin asymmetries.

Weak interaction processes, including electron capture and neutrino reactions, are fundamental for core-collapse supernova. R-process simulations require global microscopic calculations of nuclear masses. So far they have reaches a precision comparable to more phenomenological approaches. Inclusion of beyond mean field effects are necessary to further improve the description of nuclear masses in regions with sudden changes in nuclear shapes occur. These regions have been shown to play an important role in the determination of r-process abundances. An important challenge is the treatment of odd and odd-odd nuclei at a level similar to even-even nuclei.

An important extension of these approaches is the description of beta-decay rates and electromagnetic excitations. Global microscopic calculations of beta-decay rates for r-process nuclei have recently become available. They consistently account for both Gamow-Teller and first-forbidden transitions and provide an improved description of available experimental data. First-forbidden transitions are found to play an important role in the beta decay of r-process nuclei around N=126 and above in agreement with recent experimental evidence. Further improvements involve the description of deformed nuclei and a consistent treatment of odd and odd-odd nuclei.

Continued development of astrophysical models of the r-process requires an improved description of neutron capture rates. Current estimates are based on statistical model approaches. Given the extreme neutron rich conditions reached in neutron star mergers, the range of validity of statistical approaches near the neutron drip-line must be determined, and alternative reaction models developed.

Gamma strength functions are an important ingredient for the statistical description of radiative capture rates. The low-lying pygmy dipole mode in neutron rich nuclei has been observed in photo absorption reactions. For astrophysics, it is important to understand how this mode evolves with neutron excess and nuclear excitation energy. Reliable theoretical description of these excitations requires subtle effects such as couplings with complex configurations to provide fine structure of excitation spectra that allow a direct comparison with measured data. Experimental determinations of gamma strength functions involving excited states by the so-called Oslo method show evidence for the existence of an upbend at low gamma energies. The nature of the upbend (M1 vs E1) has not yet been identified. In the nuclear astrophysics context, this result shows that gamma strength functions involving excited states could be substantially different from those obtained based on ground state data. It is important to address the nature of the upbend, its dependence on excitation energy and its impact on radiative capture reactions.

Fission is expected to play a key role in the description of r-process nucleosynthesis in mergers; however, there are many uncertain aspects that need to be addressed. The region of the nuclear chart where fission sets in has not yet been conclusively identified. This may even depend on the specific channel (neutron induced, beta-delayed, spontaneous) dominating the fission during different phases of the r-process. In particular, before freeze out neutron-capture neutron induced fission is expected to be the main fission channel. It is important to extend recent advances for the description of spontaneous fission rates and yields to neutron induced fission.

An important aspect in constraining the EoS properties, and in general nuclear physics input for astrophysics simulations, is quantitative assessment of the uncertainty of the models. This necessitates development of reliable strategies to provide statistical error estimates. Since the models are often based on parameters that were fitted to sets of experimental data, the quality of that fit is an indicator of the statistical uncertainty of the model's predictions. Bayesian statistical methods provide the insight into the uncertainties of model parameters and their inter-dependencies to determine if the model employed and dataset used to constrain the model are adequate. The systematic uncertainties are associated to the spread of the calculated values due to various underlying foundations and/or parameterisations of the models that are often subject to deficiencies due to missing physics. Possible strategies include analysis of residuals, inter-model dependence, estimates using comparison with the experimental data, etc.

Given the very high cost of experimental measurements, priority lists of reactions that have the largest impact on stellar nucleosynthesis calculations are highly desirable. The process of establishing such lists using comprehensive approaches guided by theory have recently started and will yield these priority lists in the coming decade. This will be key to maximise the return on the large investments in nuclear facilities.

Observational developments

While masses of neutron stars can be measured rather precisely, present radius determinations are subject to many assumptions and uncertainties. Significant observational effort is focused on neutron star radius measurements, e.g. by determining quantities that depend on mass and radius. One approach is based on the measurement of the moment of inertia that could be achieved in five years for the PSR J0737-3039A double pulsar system. Assuming that we know the equation of state up to saturation density a measurement of the moment of inertia will constrain the radius of a neutron star within km.

Future high-precision x-ray astronomy, such as proposed by the projects NICER or ATHENA+, promise rich information from binary accretion and x-ray bursts. This will inform the inner neutron star structure and the EoS at high densities, from which the nuclear interaction in the medium can be inferred. These missions are finally allowing the study of hot intergalactic gas and the question of the cosmic baryon budget, i.e. why what we can see (through their electromagnetic interaction with photons in stars and interstellar/intergalactic gas) is only half of the baryon amount created by Big Bang nucleosynthesis.

Proposals such as GRIPS and eAstrogam establish a successor to INTEGRAL's gamma-ray spectrometer, for observing nuclear lines from interstellar gas in nearby galaxies, or from supernova and nova explosions. These compete with other (similarly-expensive) space mission proposals, and the scientific community will have to set priorities.

At long wavelengths, ground based ALMA and NOEMA instruments and their observations will continue to explore cold gas in star forming regions, measuring composition and kinematics through molecular lines. Here, some specific isotopic discriminations are possible (e.g. $^{13}C/^{12}C$, $^{16,17,18}O$ in spectra from CO molecules), thus providing access to nuclear information in molecules, as a complement to isotopic measurements of atomic or ionised gas at higher energies.

The SKA radio telescope, which is currently under construction, is expected to detect several thousands of new pulsars. This has the potential to identify the real maximum mass, by finding neutron stars with precisely determined masses significantly above $2M_\odot$ and/or a cut-off in the mass distribution. If the real maximum mass is around $2.5M_\odot$, it would represent an extremely stringent constraint for the behaviour of matter at high densities. The astrometric project THEIA might also contribute to the search of high mass neutron stars and help the radius determinations by determining the distance to x-ray binaries.

Gravitational wave astronomy represents a new observational window into the astrophysical processes in the universe. It has the potential to give new and completely independent insights about compact stars and their underlying EoS. It is only a matter of time until the first gravitational wave signal of a neutron star merger will be detected, with the potential to constrain neutron star radii and their maximum mass.

The neutrino signal of the next galactic core-collapse supernovae will provide an incomparable insight into the supernova explosion mechanism and will lead to constraints for the EoS of neutron star matter and the possible existence of a phase transition at high densities. It will be possible to determine the total energy emitted in neutrinos and the proto-neutron star deleptonisation time. In some favourable cases one could even observe the transition to a black hole.

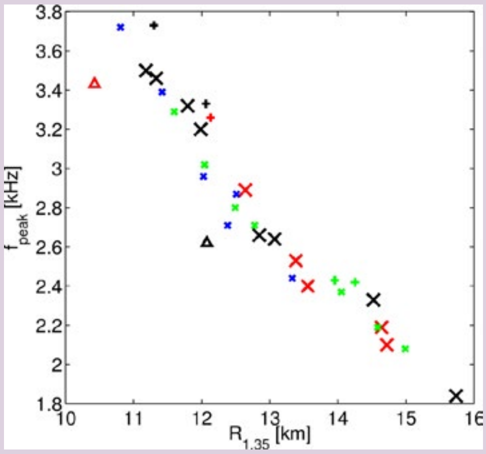
Developments in astrophysical modelling

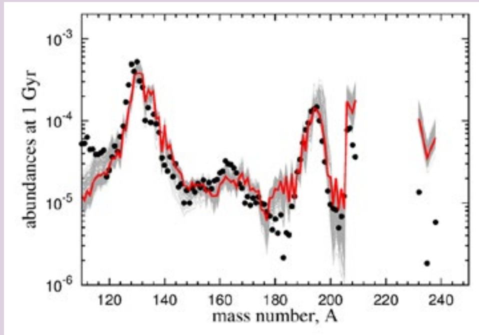
Modelling the long-term evolution of stars under the assumption of spherical symmetry has already been touched on. The current challenges are to test the accuracy and validity of the 1D approximations to astrophysical phenomena in various relevant regimes, and thus to improve or replace certain ingredients of the models to enable closer reproduction of observations. Observational data, crucial for validation of stellar models, are often limited to the core hydrogen- and helium-burning phases that comprise the vast majority of a star's life. Additionally, observational data cannot always help to distinguish the cause of a process, only an effect.

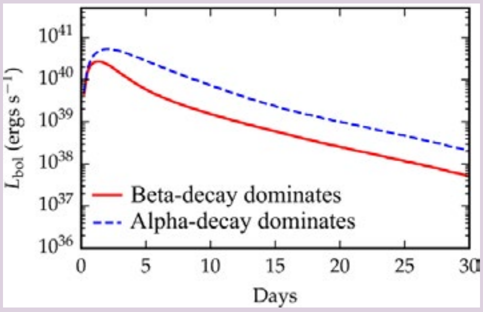
In contrast, multidimensional hydrodynamic simulations start from the relevant set of equations of fluid dynamics and can provide the missing

Box 5: Mergers and r-process nucleosynthesis

The direct detection of gravitational waves by the LIGO collaboration has opened a new window to the Universe. A future observation of the gravitational signal from a neutron star-neutron star or neutron star-black hole system will provide valuable information about the merger dynamics, which reflects neutron star properties such as its compactness. The peak frequency in the signal is directly correlated with the radius of a cold neutron star, providing a model independent determination of this fundamental property. Mergers are discussed to be a major source of r-process elements. The frequency at which mergers occur in the present Universe will be also determined by Gravitational wave detections providing constrains on the amount of material ejected in individual events. The radioactive decay of r-process material ejected in the merger could be responsible for an electromagnetic transient known as kilonova. An observation of a kilonova light curve will provide direct evidence that the r-process has indeed taken place in the merger. Other astronomical messengers (MeV gamma-ray bursts, GeV gamma-rays, positron annihilation emission) will contribute to understand such events and their aftermath. An improved description of the properties and reactions involving neutron rich exotic nuclei is fundamental to confront our predictions for the nucleosynthesis and light curves with observations.







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information concerning the physical processes operating in the region of interest. Specific problems that should be addressed include the mixing process in AGB stars that creates the ^{13}C pocket. How this pocket is formed is the most important question of the main s-process and yet is still an unsolved problem. Rotation-induced mixing (shear, meridional circulation, etc) and the transport of angular momentum are other important physical processes that can be constrained observationally from the rotation rates of white dwarfs. Simulations of the type that are needed to begin to answer some of these questions are arising and a new challenge has arisen: how to apply the knowledge gained from 2D and 3D hydrodynamic simulations to 1D stellar models in order to make better predictions of the long-term evolution of stars?

The elephant in the room of stellar modelling is the magnetic field. At present, the effects of magnetic fields are considered using simple recipes. 3D magneto-hydrodynamic simulations with a sufficiently high resolution to resolve the magnetic fields' amplification or destruction processes will still be out of reach for the next ten years. These simulations remain a long-term goal of stellar astrophysics.

Even when this is achieved, the application of stellar models is much broader than the theory of stellar evolution. The results of stellar evolution and nucleosynthesis calculations are key input for galactic chemical evolution and binary population synthesis calculations. Ideally, these calculations would include data from a multitude of stellar models spanning a large range of parameter space: initial mass, initial composition, initial rotation rate, initial binary mass ratio and initial binary separation, with a fine resolution in each parameter.

All stellar explosion models share several key goals, namely, understanding the physical mechanism of the explosion and linking the explosion phase consistently to the progenitor evolution; determination of the impact of progenitor parameters (mass, metallicity, etc.) to observables and nucleosynthetic yields, and clarifying the contribution of different stellar explosion processes to galactic chemical evolution. For thermonuclear supernova in particular, the dominant scenario for producing normal Type Ia supernovae has yet to be identified. This is urgently needed because of their prominent role as distance indicators in observational cosmology. The main challenge is to identify the progenitor system because it sets the initial parameters for the explosion process. Lacking such an observation, progress has to be made through an interplay of theoretical modelling of the evolution of possible progenitor systems, the corresponding hydrodynamic explosion simulations, the prediction of observables from such models, and detailed comparison with astronomical data. It is of particular interest to determine systematic trends of observable properties with parameters of the progenitor. This requires the parameter spaces be explored in extended sequences of simulations. Efficient numerical tools for such studies are available and the simulations will be carried out, subject to sufficient access to computational resources.

In contrast to Type Ia supernovae, progenitors of core-collapse supernovae have been observationally identified. This, however, does not imply that the progenitor problem does not introduce uncertainties. As initial conditions for the explosion simulations, the detailed structure and multidimensional shape of the star prior to the onset of core collapse has to be known to high accuracy. Thus, a main field of activity will aim at devising realistic multidimensional progenitor models that accurately capture the impact of rotation and convection. An important question is how the outcome of the collapse (neutron star or black hole) depends on the detailed properties of the progenitor star. There are indications that early ideas of a sudden transition in mass from producing neutron stars to black holes may be incorrect. We may well be dealing with islands of explodability surrounded by regions of non-exploding models.

The lower limit in mass at which core-collapse supernovae are expected remains to be determined. For the lightest massive stars (8 to 10 solar masses) two different outcomes are possible: thermonuclear explosion of the core or an electron capture supernova. Which of these is realised depends sensitively on a turbulent flame front in the core of the star that has to be treated carefully in multidimensional simulations, coupled with an accurate description of nuclear burning and electron capture processes.

The central challenge in the field of core-collapse supernova modelling, however, remains the unknown explosion mechanism. Further studies in extended multidimensional hydrodynamic simulations are required to settle this problem. These have to take into account the details of neutrino-matter interaction as well as multidimensional flow instabilities. Additional parameters that will be explored are magnetic fields and the equation of state of the forming neutron star. Such simulations will predict precise neutrino and gravitational wave signals. Measuring these in detail would be an observational breakthrough in the field providing new insight into the explosion physics. Another goal is to determine the role core-collapse supernovae play in the synthesis of heavy elements. Modelling more exotic objects, such as gamma-ray bursts, pair instability supernovae and magnetorotational supernova will remain of great interest given the forthcoming extended observational surveys of transient astrophysical sources.

The severe scale problem that astrophysical simulations have to face becomes most pronounced in simulations of supernovae. The energy input from nuclear processes takes place at scales that are small compared to the dimensions of the exploding stars. This, together with the demonstrated importance of multidimensional modelling, challenges numerical simulations. Sufficient access to high-performance computational resources, further efforts in the development of numerical techniques, and the continuity of expertise in code development are prerequisites for future progress. As nuclear processes are the most important source terms in the hydrodynamic description of the explosions, a fluid connection to the latest experimental and theoretical nuclear physics advances is essential.

Within the next few years, the understanding of the gravitational wave emission from compact object mergers will continue to grow by means of numerical simulations that will allow construction of improved parametric models. A longer-term goal, of using gravitational waves from compact object mergers to constrain the high-density matter EoS, will require connection of the results of simulations with data analysis strategies to extract the relevant parameters from a future measurement. A combination of future gravitational wave measurements and theoretical models promises to unravel the role of compact object mergers for the enrichment of the universe by heavy r-process elements and thus to answer the question whether or not compact object mergers are the dominant source of heavy r-process elements. The key steps towards an answer are a clarification of the merger rate, of the average amount of ejecta per merger event and of the robustness and details of the r-process in the merger outflows.

A better constraint of the local merger rate will be provided by the frequency of gravitational wave detections. The robustness of the r-process will be settled by network calculations based on improved hydrodynamcial models including advanced methods of neutrino transport physics. The exact thermodynamical conditions are relevant so that nuclear network studies can identify the detailed path of the r-process and the most relevant nuclear reactions, clarifying for instance the role of fission processes. Challenges are the development of improved numerical tools, availability of sufficient computational resources and advances in the description of nuclear reaction rates.

Progress in determining amount of ejecta per merger event will emerge from improved hydrodynamical models, further theoretical, experimental and observational constraints on the neutron-star EoS, and possibly the detection of electromagnetic counterparts. In the case of the latter, interpretation will rely on detailed numerical models of the outflows and nuclear network calculations. Additional insights into the role of mergers will arise from population synthesis models and chemical evolution models, which will in particular shed light on the early enrichment. This may clarify whether compact object mergers are responsible for the early enrichment of the Galaxy, or if alternative sites such as magneto-hydrodynamical jets in core-collapse supernovae should be invoked.

Hydrodynamical simulations face challenges in modelling the exact conditions in the ejecta. High-resolution hydrodynamical calculations with an appropriate treatment of neutrino transport physics will be required to nucleosynthetic yields produced in those outflows. The initial conditions of the neutron star-torus or black hole-torus system forming after the merger depend on the preceding dynamics of the merger. From these remnants additional matter becomes unbound by neutrino winds or magneto-hydrodynamical effects and contributes to the total nucleosynthesis yields of compact object mergers. Thus, it will be particularly important to consistently connect hydrodynamical merger calculations with long-term evolution models of the ejecta that include neutrino transport and magneto-hydrodynamical effects. Neutrinos as well as magneto-hydrodynamical effects also play a role during the dynamical phases of the merger and thus affect the details of the prompt-ejecta nucleosynthesis and associated electromagnetic counterparts.

Perspectives

Due to the great diversity and strong interdisciplinary character of the field, nuclear astrophysics requires a wide range of experimental facilities, from major international laboratories to smaller university-based centres. Theory too plays a strong role in nuclear astrophysics, as it is necessary to connect experimental observables to astrophysically relevant quantities, and is essential in providing properties of nuclei that are not accessible due to current experimental limitation. Sufficient access to supercomputer facilities is becoming ever-more important, particularly for stellar modelling, where improved descriptions of physics and the intrinsic multi-dimensional nature of nuclear processes are key.

Significant investment is being made in larger facilities. The worldwide unique multifaceted approach that will be delivered by FAIR opens a new era for nuclear astrophysics and promises to deepen our understanding of the Universe and the objects therein. FAIR and the instrumentation of the NUSTAR collaboration will provide unparalleled access to unstable nuclei far from stability, in particular to the heavy neutron-rich r-process nuclei around N=126. CBM will study the properties of matter at the high densities achieved in neutron stars and will constrain the supernova equation of state. With its ability to produce high rates of hypernuclei, PANDA will contribute to our understanding of the nucleon-hyperon and NN-hyperon interactions. The APPA collaboration will explore the behaviour of matter, in storage ring experiments, under the extreme electromagnetic fields achieved on neutron star surfaces and, in ion-beam and laser experiments, under the astrophysical conditions expected in stellar plasma and in gaseous planets.

We underline the unique opportunities that the SPIRAL2 and MARA facilities will offer in the very near future to study the rp-process, arising from the intense stable beams that they will deliver. We recognise the necessity for the ISOL facilities to expand their coordinated approach in the framework of EURISOL-DF to beam development, as lack of specific radioactive species of sufficient intensity is a major limitation.

The ELI-NP facility at Bucharest, which will become operational as a user facility in 2019, will provide high-power laser pulses and high-intensity narrow-bandwidth gamma beams. Studies of laser-driven nuclear reactions in controlled plasma conditions will become possible together with measurements on photodissociation reactions with unprecedented precision. This will provide new research opportunities for the nuclear astrophysics community in Europe.

Laboratories based at universities and similar sized institutions maintain a vital role in nuclear astrophysics. Often delivering a significant breadth of (mainly stable) beam species, with low-energies well matched to astrophysics, they continue to maintain very high relevance. The rapid developments in astronomical observations and astrophysical models drive a need for high precision cross section measurements. These, and other high impact studies, reflect the strong programme of nuclear astrophysics research carried out at small-scale facilities. Indeed, the volume of science deliverable solely by large facilities is limited, such that without the smaller facilities, beam time would be in even greater demand than it is now. Together with their larger counterparts, small facilities provide the vital training of the next generation of researchers on the broad range of techniques necessary to run and analyse experiments. The operational mode of small facilities is often coupled to industrial, commercial and medical applications, and thus small facilities naturally provide opportunities for knowledge exchange and engagement.

A particularly important facility is the Laboratory for Underground Nuclear Astrophysics (LUNA) at Gran Sasso. Its unique location has made it a world-leading facility that has performed high impact nuclear reaction studies of astrophysical importance, at the relevant stellar energies.

A key issue in experimental nuclear astrophysics research is the availability of high quality target material, tailored for the special envisaged experiment. Radioactive targets, in particular, require significant efforts for the production of the isotope, its chemical separation and purification as well as complex target manufacturing and handling.

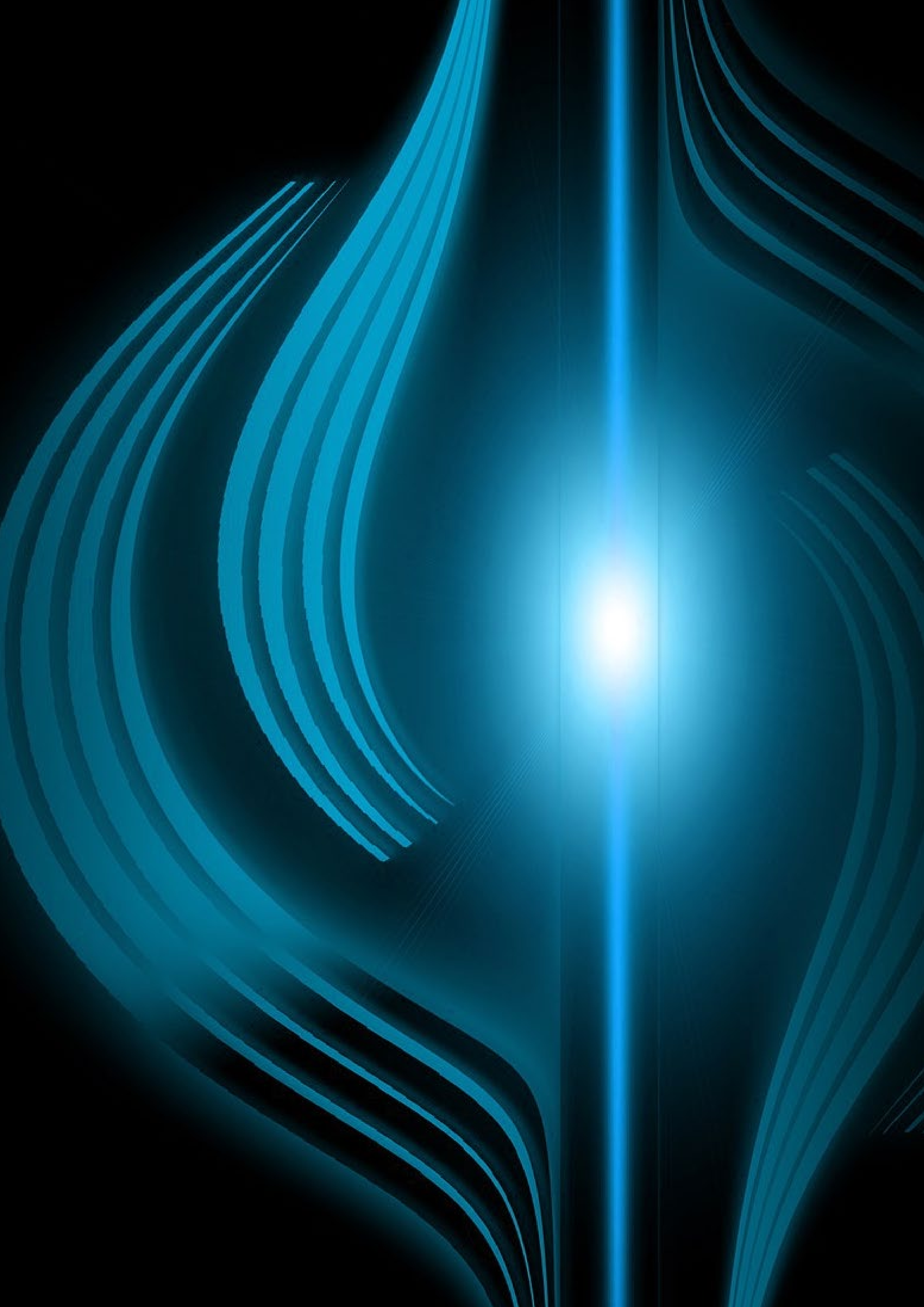
Theoretical nuclear astrophysics deals with extrapolations of experimental data to astrophysically relevant energies or temperatures. This couples large nuclear networks with sophisticated astrophysical models to allow determination of key experimental observables that fully exploit the possibilities offered by the experimental facilities. Given the broad range of techniques needed and the access to powerful computers it is essential to have a comprehensive education programme to train the next generation of researchers.

The collective efforts of experimentalists, theorists can guarantee continued European leadership in nuclear astrophysics, and will supplement the strong programmes in astrophysics, cosmology and astroparticle research. Science policy makers, and evaluations of current and future astronomical capabilities, will benefit considerably from the input of the nuclear physics community to ensure that the wider benefits are understood.

Recommendations

- We strongly support the upgrade of LUNA with a multi-MV accelerator and associated infrastructure, allowing access to a new range of nuclear reactions.
- We strongly recommend that dedicated nuclear astrophysics programmes at universities and small-scale facilities be supported to enable them to continue and extend their high impact science. We furthermore recommend that access to such facilities is maintained through the transnational access programme
- We strongly support the completion of the FAIR facility, and its exploitation by the four experimental pillars APPA, CBM, NUSTAR and PANDA.
- We strongly support the full completion of the next generation of radioactive ion beam facilities, including HIE-ISOLDE, SPES-INFN and SPIRAL2. We highly recommend the implementation of phase 3 of HIE-ISOLDE and an upgrade of the GANIL CIME cyclotron, enabling the study of capture reactions of astrophysical importance. The installation of a new storage ring at HIE-ISOLDE is also recommended. In the longer term, we strongly support progress towards EURISOL.
- We strongly recommend that the instrumentation needed for the implementation of the ELI-NP research programme be built and the suggested experiments are performed with high priority.
- We recommend the formation of a target preparation network and the support of target producing research groups to enable successful future experiments.
- We strongly recommend the continuation and extension of the training efforts, at large and small-scale facilities, to guarantee enough skilful people at future facilities.
- We recommend support for ECT* at Trento to continue its leading role training young researchers in theoretical nuclear astrophysics.

- We recommend that the nuclear astrophysics community and funding agencies engage more proactively and effectively with the bodies influencing funding decisions on astronomical (both space and ground-based) facilities.



5

SYMMETRIES AND FUNDAMENTAL INTERACTIONS

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5. SYMMETRIES AND FUNDAMENTAL INTERACTIONS

INTRODUCTION

The presently known fundamental interactions governing Nature and the Universe from the largest to the smallest distances display symmetries and symmetry breaking. Noether's theorem links symmetries with conservation laws which depend on the interaction type. It is well known that, for example, conservation of momentum and angular momentum rest on isotropy of space and the invariance of the laws of physics under translational and rotational transformations. On the other hand, for various apparently conserved quantities like lepton number an underlying symmetry is absent or yet unknown, motivating theoretical developments and experimental searches.

Four fundamental interactions: electromagnetic, weak, strong and gravitational, are well identified. The first three have been successfully included in the Standard Model (SM) of particle physics while gravity has so far resisted all attempts to be cast into a viable quantum field theory together with the other interactions. We know a set of basic constituents, leptons, quarks and gauge bosons, which form all known matter and the interactions between them as described by the SM. The recent discovery of the Higgs boson has in many ways completed the SM.

Nuclear Physics has played a major role in finding and establishing the laws which govern the physics at the most fundamental level. One of the most notable examples is the maximal violation of spatial inversion symmetry, parity *P*, in the weak interaction. Shortly after the discovery of *P* violation also the combined *CP* symmetry (*P* and charge conjugation *C*) was found to be broken. These discoveries have triggered intense research on symmetry violations, including those of time reversal (*T*) symmetry. In Quantum Field Theory (QFT) *C*, *P*, and *T* are related by the *CPT* invariance theorem resting among other assumptions on Lorentz Invariance (LI).

Today, fundamental physics is located interdisciplinary between nuclear, atomic, particle and astrophysics. Major advances in the state-of-the-art technology have made novel approaches feasible. The most accurate technologies from various research fields are employed to prepare the fundamental systems under study. They range from low-energy particles, ultracold atoms, ions and molecules (with major applications also in chemistry, quantum information processing and metrology), through novel sensors and radiation detectors (also used for medical applications), to the analysis of complex sets of data and extracting the underlying information (e.g. big data, computing, pattern recognition, ...). At the same time the most advanced theoretical and calculational techniques are developed and applied by nuclear, atomic and particle theory to perform ever more stringent comparisons between theory and observation, and to establish discrepancies. While nuclear and particle physics have developed along different pathways, technologies have usually been shared. We find today, in particular also from high energy particle physics, an increasing interest in complementary approaches to the same most fundamental questions and a growing appreciation for key experiments in the intensity and precision physics domain (see Box 'Precision Challenge') sometimes sensitive to high energy and mass scales exceeding those for the present and future collider experiments. Nuclear physics and its technologies play crucial roles in many such experiments. Theory is about to develop common languages, for example in the form of the Standard Model Effective Field Theory (SMEFT), which can systematically parametrize any new physics at high energy scales and connect experiments at different lower scales. But precision physics does not stop there and also most sensitively probes the realm of new physics at low mass scales with very small couplings as, for example, in the case of axion-like particles (ALPs). The underlying theme is to find new particles, interactions, and symmetries or symmetry violations which could help overcoming the shortcomings of our present understanding and which could give signs for physics beyond the SM. Along this path, many experiments also aim at testing some of the most basic assumptions of our theories today, in particular LI, *CPT* symmetry and permutation symmetry connected to the spin-statistics theorem (SST).

Quantitative understanding of measurements at the highest levels of precision and accuracy is a necessary key ingredient for a more complete description and understanding of Nature. The research in the field proceeds along two main routes: precision determinations of fundamental parameters and searches for deviations from the SM predictions. Precision measurements of, for example, masses, mixings and coupling constants are ideally carried out in complementary

Box 1: Precision Challenge

Studies of symmetries and in particular observation of symmetry violations ("symmetry breaking") rely on precision measurements of physical observables and require ingenious experimental conditions and hardware and an unambiguous description of the underlying physics: celebrated examples are the discoveries of parity (*P*) and charge-parity (*CP*) violation over 50 years ago, which were largely unexpected and fundamentally changed our understanding of Nature.

Precision experiments often demand high statistics, long measurement time and utmost control of experimental parameters. Improvements are usually achieved in iterations, where a next-generation set-up exploits the experience from previous measurements in an attempt to overcome limitations or shortcomings of the previous versions by developing novel approaches. It is also beneficial to perform independent measurements of the same physical quantity in diverse systems or with different experimental devices – leading to varying systematic errors – in order to scrutinize the validity of the results. Eventually a robust theoretical model is required for the interpretation of the outcome or the determination of its significance. Recently, the Standard Model Effective Field Theory is receiving more attention as a model-independent approach allowing the systematic intercomparison of many experiments (see Box 'Standard Model Effective Field Theory'). The interplay between experiment and theory stimulates the development of both theoretical concepts or models and of (beyond) state-of-the-art instrumentation.

In our quest to better understand the structure of matter and fundamental interactions, the *precision frontier* is complementary to ever higher energy and intensity experiments and is a promising strategy towards new discoveries.

approaches to allow overdetermination of theory parameters and cross-checks. With improved experimental precision, sensitivity and stability, long-duration observations can be turned into searches and tackle the question of time dependence of fundamental "constants", the constancy of which is often taken for granted. Another class of sensitive searches can be performed where the predicted value of an observable is negligibly small or even zero in the standard theory. Examples include permanent electric dipole moments (EDM) of particles, neutrinoless double beta ($0\nu\beta\beta$) decay or charged-lepton flavour violation (cLFV), so that verified experimental signals translate into discoveries.

Despite the tremendous and highly encouraging success of the present SM, various observations point to the need for its extensions. The above-mentioned difficulty to include gravity is one example. A number of observations, astrophysical and astronomical, pose enormous challenges, such as the likely existence of Dark Matter, accelerating expansion of the Universe, and Baryon Asymmetry of the Universe (BAU) with matter by far outnumbering antimatter. Observations call for baryon number *B* violation, connected or not to lepton number *L* violation, and additional *CP* violation which is not found to be sufficiently strong in the SM although sufficiently strong CP violation is readily obtained in many of its extensions. Search experiments involve the full spectrum of particles from neutrinos, charged leptons to hadrons to stable and radioactive ions, and molecules. It is important to recall that *CP* violation naturally appears in quantum chromodynamics but must be unnaturally small as proven by the absence of finite values of permanent hadronic EDM at least at the level of sensitivity obtained experimentally so far. Also improved *B* and *L* violation searches push the limits and continue to provide some of the most stringent bounds on models of new physics.

This report on "Symmetries and Fundamental Interactions" presents a short overview and status of the vibrant research activities and discusses the prospects and most promising new directions, especially for the European research landscape with its present and future facilities.

SM PARAMETERS

Leptons

There are only a few parameters which characterize leptons, i.e. masses, mixing angles, lifetimes, charges and magnetic moments. As spin 1/2 particles they do not possess higher-order electromagnetic moments. It is an observational fact that the value of the charge is quantized $\pm e$, or 0, which is far from being understood. Open issues include the difference in mass scales between charged and neutral leptons, and the specific structure of the neutrino mass matrix which is investigated in neutrino oscillation experiments.

Neutrinos

More than a dozen experiments with atmospheric, solar, accelerator and reactor neutrinos have clearly proven that neutrinos from one flavour, e.g. an electron neutrino ν_e from the nuclear fusion in the core of the sun, change into another neutrino flavour, e.g. a muon ν_μ or tau neutrino ν_τ, in-flight. This requires neutrinos to have non-zero masses and to exhibit a non-trivial mixing between neutrino mass states ν_1, ν_2 and ν_3 and neutrino flavour states ν_e, ν_μ and ν_τ. This discovery of neutrino oscillations opened the door to the studies of the neutrino properties which are very important for nuclear and particle physics, as well as for astrophysics and cosmology. Unfortunately, neutrino-oscillation experiments are not sensitive to neutrino masses but to the differences of squared neutrino masses Δm^2_{ij} (i,j=1,2,3) and to the parameters $U_{\alpha i}$ (α = e, μ, τ) of the mixing matrix. Currently we know Δm^2_{21} and the mixing angle θ_{12} from solar and reactor neutrino experiments, $|\Delta m^2_{32}|$ and θ_{23} from atmospheric and accelerator neutrino experiments, and the 3rd mixing angle θ_{13}, determined mainly by reactor neutrino experiments (Daya Bay, RENO, Double Chooz).

An important question – in particular to explain the smallness of the neutrino masses – is the mechanism for neutrino-mass generation. Neutrino masses are at least six orders of magnitude smaller than the masses of the other fundamental fermions. Therefore we expect that there might be something beyond the usual Yukawa coupling to the Higgs, and thus physics beyond the SM, required to explain the tiny neutrino masses, for example via the so-called see-saw mechanism. A missing experimental result in this respect is the mass hierarchy: depending on the sign of Δm^2_{32}, or Δm^2_{31}, respectively, $m_3 := m(\nu_3)$ is the largest or the smallest of all neutrino masses (see Figure 1). This hierarchy will be determined with accelerator or reactor neutrinos in long-baseline experiments or with atmospheric neutrinos using neutrino telescopes. To analyse the data from present and future high-precision accelerator neutrino experiments nuclear physics will be very important to understand the neutrino nucleus cross sections.

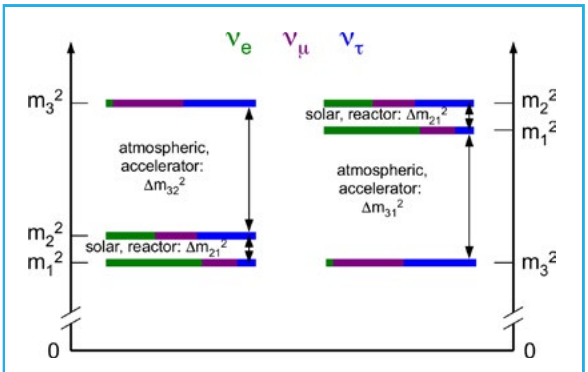


Figure 1: Possible hierarchies of neutrino masses: normal (left) and inverted (right) hierarchy.

Neutrinos are believed to outnumber atoms in the Universe by nine orders of magnitude. Therefore, even tiny neutrino masses contribute to the Dark Matter as Hot Dark Matter component and influence the evolution of the Universe. The direct determination of the neutrino mass scale by the study of the kinematics of weak decays is usually pursued by investigating the endpoint region of the tritium beta-decay spectrum (KATRIN). Recently the successes of cryobolometer and magnetic microcalorimeter techniques drew attention to the electromagnetic deexcitation spectrum after ^{163}Ho electron capture (ECHo, HOLMES, NUMECS). These direct searches for the neutrino mass scale in the sub-eV range are complementary to cosmological analyses and searches for $0\nu\beta\beta$ decays.

In contrast to all other fundamental fermions, neutrinos are neutral. Thus they could be their own antiparticles (Majorana neutrinos) violating *L* conservation. Nearly all neutrino mass models beyond the SM require Majorana neutrinos and no symmetry is known related to *L* conservation. The search for $0\nu\beta\beta$ decay is a sensitive test for *L* violation. A positive signal would definitively be related to new physics which could be explained by neutrinos being Majorana particles or by some other *L* violating effects. The second-order weak $0\nu\beta\beta$ transition can occur without neutrino emission if neutrinos are their own antiparticles. The transition rate is sensitive to the weighted sum of all neutrino mass states contributing to the electron neutrino, complementary to the observable mass in direct beta-decay searches. Unfortunately, in addition to unknown Majorana phases of the neutrino mixing matrix and the unknown neutrino hierarchy, the calculation of the nuclear matrix elements still introduces significant uncertainties to this way of determining the neutrino mass scale. Currently, half-life sensitivities of 10^{26} y for $0\nu\beta\beta$ decay are under investigation requiring ultra-clean, 100 kg-scale isotope-enriched detectors. In Europe, major efforts are under way with installations in the underground laboratories of Gran Sasso, Modane and Canfranc. The Majorana nature of neutrinos, together with heavy right-handed neutrinos predicted in most neutrino-mass theories beyond the SM and with leptonic *CP* violation, can provide via leptogenesis the sought-after source for BAU.

The SM describes three flavour and three mass states of neutrinos. There are several hints (e.g. the so-called "reactor anomaly") that there could possibly be a forth, sterile neutrino state, which does not couple to W- or Z-bosons. With short-baseline neutrino-oscillation experiments or with precision studies of the endpoint spectra of tritium beta decay or ^{163}Ho electron capture the existence of light sterile neutrinos will be checked. Sterile neutrinos with keV masses are an interesting candidate for Warm Dark Matter.

Charged leptons and fundamental constants

Properties like masses and magnetic moments of free and bound charged leptons are measured in precision experiments and also used in determinations of additional fundamental constants. Consistency of independent results provides further tests of fundamental theories. Some dimensionless constants, such as the fine structure constant α, the weak mixing angle $\sin^2\Theta_W$ or the proton-to-electron mass ratio, are of particular interest.

Since the original calculations of Bethe, Feynman and others of the hydrogen Lamb shift, quantum electrodynamics (QED) calculations of a number of observables have advanced to the point where uncertainties of fundamental constants, or contributions from the strong interactions through hadronic vacuum polarization, or hadronic light-by-light scattering limit theoretical accuracy.

The Rydberg constant R_∞ is the most precisely determined fundamental constant; it links the fine structure constant, the Planck constant, and the electron mass. Because it is currently measured only in H and D, its value is nearly 100% correlated with the proton and deuteron charge radii. Because of the proton radius discrepancy between muonic and electronic determinations (see below), the value of R_∞ is currently under debate. In near future, laser spectroscopy of other calculable systems, such as helium ions, can provide independent determinations of R_∞ when combined with the respective nuclear radii and polarizabilities.

The magnetic moment anomaly $(g_\mu\text{-}2)/2$ of the muon has been measured with 5×10^{-7} precision at BNL and a 3-4σ discrepancy with the calculated SM value persists (see box 3 in WG1). A new experiment with a five-fold improved precision on g_μ-2 will start data taking at FNAL soon. Another g_μ-2 project is being pursued at J-PARC. Since the muon is 200 times heavier than the electron, its anomaly is intrinsically much more sensitive to hadronic corrections and to the existence of as yet unknown hypothetical heavier particles.

Comparison of measurements with SM calculations for the magnetic moment or g-factor of the free and the bound electron in hydrogen-like systems provides the most stringent consistency tests of QED. Therefore, the determinations of g-factors (see Figure 2) will be continued at high-precision levels with the potential to discover new physics. The fine structure constant α determines the strength of the electromagnetic interaction. It enters as an expansion parameter in QED. An example is the magnetic moment of the electron which permits the present best determination of α at the 10^{-10} level based on the g_e-2 measurement of a single electron in a Penning trap at Harvard and QED calculations performed up to the α^5 order. The most accurate value of the electron mass m_e (in amu) with a relative precision at the 10^{-11} level is obtained by a comparison of state-of-the-art bound-state QED calculations and precise measurements of the g-factor of the bound electron in $^{12}C^{5+}$ at Mainz. Furthermore, the superb precision achieved in these recent experiments makes them sensitive to hypothetical particles, complementary to the muon g-factor. Of course, a strong theoretical effort and thorough scrutiny is required.

Bound-state QED in the strong-field regime ($Z\alpha$ close to unity with Z being the nuclear charge) is explored by x-ray spectroscopy for Lamb-shift measurements, by laser spectroscopy of hyperfine and fine structure, and by microwave spectroscopy of magnetic substates for bound-electron g-factor determinations. A careful comparison of results from ions in different

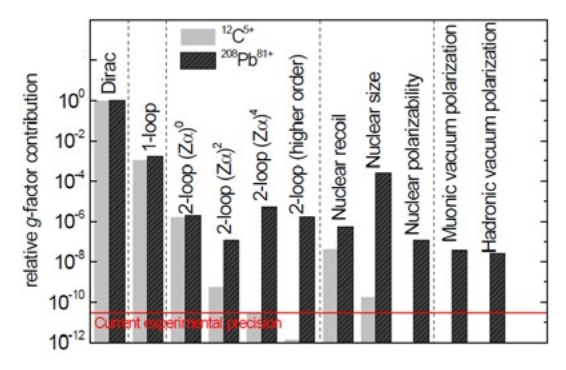


Figure 2. Magnitudes of the relevant theoretical contributions to the bound electron g-factor in $^{12}C^{5+}$ and $^{208}Pb^{81+}$: The leading Dirac contribution, one- and two-loop bound-state-QED corrections, nuclear and muonic effects. The present experimentally achieved precision in $^{12}C^{5+}$ is indicated with the red line. A similar precision should be reached for Pb.

charge states (H-, Li-, B-like) would allow for disentangling nuclear structure and QED effects to a high degree. The highest accuracy is reached with cooled highly charged ions stored in precision traps from electron beam ion trap (EBIT) sources or accelerator facilities like the ESR storage ring at GSI with subsequent deceleration such as proposed for HITRAP. Experiments in storage rings (CRYRING, ESR, HESR and SIS100 at GSI/FAIR) offer wide Doppler tunability and therefore access to laser spectroscopy on heavy highly charged ions, in particular, when combined with novel XUV laser sources.

Another well-established phenomenon in strong-field QED is electron-positron-pair creation during scattering of two nuclei. When the total charge Z′ exceeds the supercritical value Z′ ≥ 173, the system enters the unperturbative QED regime, which should lead to, among other phenomena, a significant enhancement of pair creation. This enhancement has not yet been observed and requires further investigation.

Precision spectroscopy of the 1S-2S transition and the ground-state hyperfine splitting (HFS) of muonium determines the mass and the magnetic moment of the muon, impacting the determination of g_{μ}-2 and providing an independent QED test, possible access to the fine structure constant, the Rydberg constant and various SM tests, such as that of charge equality between the two lepton generations. Efforts are ongoing to perform a new HFS experiment at J-PARC aiming at an improvement in relative precision from 1.2×10^{-8} to 10^{-9} and a new 1S-2S measurement at PSI to improve from 4×10^{-10} to 10^{-11}.

Further, stringent QED tests are performed with positronium. The spectroscopy of the 1S-2S transition is under way in several projects worldwide. They aim at improving the relative precision to 10^{-10}. The possibility of another two orders of magnitude would permit an independent determination of the Rydberg constant. A determination of the 2S HFS aims at 10^{-5} or better in order to shed light on the current discrepancy of 3.6σ between the most precise measurements and bound-state QED calculations for this system. Considerable effort will be needed on the theoretical side in order to obtain the adequate accuracies.

The weak coupling constant G_F has been determined with $5 \cdot 10^{-7}$ precision from a 10^{-6} measurement of the lifetime of positive muons by the MuLAN collaboration at PSI together with two-loop QED calculations and including electron mass corrections. The muon lifetime is the most precisely measured lifetime of any particle or state. The electroweak sector of the SM is determined by G_F, the fine structure constant α and the Z-boson mass. It is a cornerstone in weak-interaction physics and tests lepton universality even in semi-leptonic decays, including nuclear beta decay. The extraction of G_F from experimental data assumed the validity of the SM. Planned weak-interaction studies and searches for new physics beyond the SM using neutron and nuclear decays which aim at a 10^{-4} precision must take into account that the model-independent determination of the weak coupling from muon decay is less constrained, down to only about $3.6 \cdot 10^{-4}$.

Baryons

Precise measurements of baryon properties provide relevant information on fundamental interactions. On the one hand, precise measurements in nuclear β decays enable probing the structure of the weak interaction. At a high-precision level, electromagnetic and strong interaction effects have to be considered. On the other hand, precise measurements of certain nuclear parameters permit improving QED tests and determining fundamental constants in a way largely unaffected by nuclear-structure uncertainties.

Semileptonic decays

In a general description of nuclear and neutron β decay, the decay probability can be written as a function of the spin of the parent, the momenta of the electron (positron) and (anti)neutrino and the spin of the electron (positron). It contains observable correlations and parameters, e.g., the electron-neutrino momentum correlation *a*, the Fierz parameter *b* influencing the electron spectral shape, the beta-asymmetry parameter *A* between nuclear polarization and electron momentum, and the neutrino-asymmetry parameter *B*. Also triple correlations are being studied, especially the time reversal violating correlations between nuclear spin, electron and neutrino momentum (*D*) or nuclear spin, electron momentum and spin (*R*). In practice, the neutrino momentum cannot be measured. It is therefore necessary to measure the recoil momentum of the nucleus to determine the full correlations.

The accuracy of measurements is often hampered by the low kinetic energies of the recoiling nucleus. In the study of nuclear decays, major progress has been achieved recently by using atom and ion traps to store the radioactive nuclei in vacuum, allowing one to accurately measure the direction and energy of the recoil. The correlation coefficients, *a* through *R*, depend on coupling constants and nuclear matrix elements.

Box 2: Standard Model Effective Field Theory

In recent years, an overarching framework has been developed for searches for new physics: the Standard Model Effective Field Theory (SMEFT). It can be used to put model-independent limits on coupling constants that parametrize physics beyond the SM and to correlate experimental data for different processes. As such, it provides a fruitful meeting ground of experiment and theory. In particular, the SMEFT has become a tool of choice for the analysis of high-precision searches for symmetry-breaking observables at low energy as well as for studies of new physics at colliders. Its basic idea is the following: in searches for new physics assumed to originate from a yet unknown fundamental theory at some high-energy scale Λ, the SM should be regarded as an effective field theory, which is valid up to an energy scale of about Λ/10. In natural units, $\hbar = c = 1$, the action is dimensionless and therefore the Lagrangian density has mass-dimension four. The SM contains only renormalisable operators of mass-dimension two and four. The effects of new physics can then at low energy be described model-independently with an effective Lagrangian density of the form

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$$

where $\mathcal{L}^{(4+k)}$ contains all possible operators of dimension 4+K made up of the SM fields. New physics gives rise to higher-dimensional operators, suppressed by powers of the high-energy scale Λ. Any fundamental quantum field theory at high energy, when systematically expanded in inverse powers of Λ, results in such an effective field theory at lower energy, with specific values of the coefficients that multiply the higher-dimensional operators. Remarkably, only one dimension-five operator exists, which, after electro-weak symmetry breaking, leads to a Majorana mass for the neutrinos. There are, however, many dimension-six operators in $\mathcal{L}^{(6)}$, but often only a very limited number contribute to specific low-energy observables. As an example, a dimension-six operator would shift the anomalous magnetic moment of the electron by an amount of order $O\left(m_e^2/\Lambda^2\right)$. The agreement of experiment with QED calculations translates into a lower bound on Λ of order 10 TeV, implying that QED is valid to this energy scale at least. Dimension-six operators have been studied in, for instance, neutron and nuclear beta decay, hadronic and atomic electric dipole moments, and lepton-flavour violating processes.

For pure Fermi or Gamow-Teller β transitions these coefficients are independent of the matrix elements and thus, to first order, of nuclear-structure effects; they depend only on the spins of the initial and final states. The description of β decay, and of the weak interaction in general, in terms of exclusively vector (V) and axial-vector (A) interactions, i.e. the V-A theory as low-energy effective part of the SM, found its origin in measurements of the beta-neutrino correlation coefficient *a*. The discovery of parity violation was made from the observation that the beta-asymmetry correlation coefficient *A* is non-zero. In general, choosing the appropriate initial and final states in Fermi and Gamow-Teller β transitions and accordingly selecting the correlation coefficients, one can either accurately measure the g_A/g_V coupling-constant ratio or search for symmetry violations or yet undiscovered scalar (S) and tensor (T) contributions. Such searches are now under way at laboratories around the world, aided by the advent of new high-intensity sources of cold and ultracold neutrons and by the ability to trap significant numbers of radioactive atoms or nuclei.

For neutrons, many landmark results have been obtained at the ILL which today provides the world's highest intensity cold neutron beams. A new type of beam-station for the measurement of neutron decay angular correlations, called proton and electron radiation channel (PERC) is under construction at FRM II and a successor installation is under discussion for a fundamental-physics beamline at the ESS. Detailed calculations show that the spectra and angular distributions are expected to be distortion- and background-free on the level of 10^{-4}.

Angular correlations of momenta and spins of particles emitted in semileptonic decays of elementary particles and nuclei allow for direct searches for beyond SM phenomena as all observables (correlation coefficients) depend explicitly on the exotic interactions. The sensitivity to these interactions varies from one transition to another and between correlation coefficients so that the best constraints are obtained in combined analyses including those of pion, neutron and nuclear decays. Recently the model-independent SMEFT approach has been used to analyze such processes (see Box 'Standard Model Effective Field

Theory'). Typical experimental sensitivities at the 10^{-3} level give access to energy scales of a few TeV for beyond SM physics complementary to collider searches. Present experimental accuracies of the correlation coefficients in semileptonic decays are at the level of 10^{-2} – 10^{-4}. Efforts are ongoing to improve these accuracies by an order of magnitude. Soon a large number of such results will become available as major efforts are under way in Europe and North America. Precise values for the electron-neutrino correlation $a_{\beta\nu}$, the Fierz parameter b_n, the beta-asymmetry parameter A_β, and the neutrino-asymmetry parameter B_ν are expected. The correlations involving the electron spin are highly attractive, especially because of their linear dependence on the small exotic couplings. However, so far they remain largely unexplored because of experimental difficulties. This could change in the future with the newly proposed BRAND experiment to measure simultaneously seven electron-spin-dependent correlations in neutron decay. The ideal facility for this novel approach will be the fundamental-physics cold-neutron beamline at the upcoming ESS. Besides with the neutron, *b* will be measured via the shape of nuclear β spectra. The main idea in existing projects is the confinement of the source inside the electron-detection setup to avoid systematic effects related to electron scattering. Nevertheless, improvements in β-decay detection and simulations are mandatory to reach a precision level below 0.5% on *b*. The quadratic dependence of the β-ν correlation coefficient *a* in exotic couplings implies that, to remain competitive with LHC, a precision level of 10^{-3} or better should be reached. Addressing this challenge requires experimental devices with advanced control of systematic effects, a goal being pursued in several projects. Depending on the availability of long beam periods at dedicated facilities like ISOL@Myrrha and building on the advances in experimental techniques, more projects might be developed in Europe. On the theoretical side, the consideration of radiative and recoil corrections is mandatory. At this level of precision, experiments also become sensitive to strong-interaction effects. For instance, the β-spectrum shape depends on a weak-magnetism term whose magnitude is poorly known, especially for nuclei with mass numbers larger than 40, where a large component could be responsible for the already mentioned reactor neutrino anomaly.

Quark mixing matrix

It is well established that the quark weak-interaction eigenstates are mixtures of their mass eigenstates, described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The unitarity of this matrix, studied for more than 25 years, is now confirmed at the $5.5{\cdot}10^{-4}$ level thanks to major experimental and theoretical efforts, which have allowed a precise determination of the dominant matrix elements V_{ud} and V_{us}. In particular, a careful study of 20 superallowed Fermi transitions, i.e. half-life $T_{1/2}$, branching-ratio *BR* and mass *M* measurements and computation of theoretical corrections [isospin symmetry breaking (ISB) δ_c, radiative corrections (δ_R', δ_{NS} and Δ_R)] to assess their corrected *Ft*-values, has enabled the determination of V_{ud} to a relative precision of $2.2{\cdot}10^{-4}$ (see Figure 3): V_{ud} = 0.97417(21).

In Europe and worldwide, future plans include:

- Further improvements of experimental data related to superallowed Fermi transitions, to reduce uncertainties on the 14 best studied decays and add new candidates in the previous set, and to improve theoretical corrections, especially the Coulomb correction δ_c, which dominates the uncertainty. Spectroscopic measurements for higher-*Z* nuclei are advised, as well as measurements in "couples" of superallowed mirror transitions.
- Measurements with the neutron which decays through a mirror transition. In this way, a determination of $|V_{ud}|$ is based solely on two experimental inputs, e.g. the neutron lifetime, and a measurement of one angular-correlation coefficient. The advantage here is the absence of nuclear corrections. However, the two most precise lifetime measurements with ultracold and cold neutrons, respectively, τ= 878.5(8) s and 887.7(23) s, differ by several standard deviations. Thus, if a consistent val-

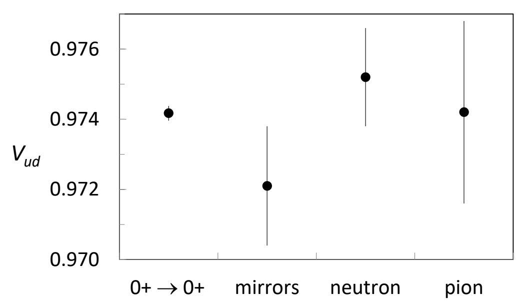


Figure 3. Updated values of V_{ud} from pure Fermi transitions, β transitions of isospin T=1/2 mirror nuclei, neutron decay and pion β decay.

ue for $|V_{ud}|$ is to be derived from neutron decay, the most pressing objective must be to perform more accurate lifetime experiments and to further reduce the uncertainty in correlation coefficients until it is limited by the theoretical uncertainties. Efforts in Europe as well as abroad are under way aiming to push the precision into the few 10^{-4} region. The European lifetime experiments are PENeLOPE, Gravitrap, Hope, τSPECT, and an experiment by Ezhov *et al.*, instruments for correlation-coefficient measurements include PERKEO, aSPECT, and NoMoS.

- Measurements in mirror nuclear decays. The V_{ud} value deduced from the study of mirror decays, 0.9719(17), was published in 2009 and is almost a factor of 10 less precise than the result obtained from pure Fermi transitions. As for the neutron decay, the main difficulty here is the need for precise values of the mixing ratios which can only be obtained from correlation measurements in the β transitions. These parameters are the least well-known quantities currently preventing improvement in the precision on V_{ud}. Recent precise measurements of $T_{1/2}$, *BR* and *M*, performed mostly at IGISOL, ISOLDE, GANIL and TRIUMF, could not as yet improve on the precision of the updated V_{ud} value, 0.9721(17), emphasizing the crucial need for correlation measurements. In Europe, two projects are currently being pursued:
  - Measurement of the β-asymmetry coefficient *A* in the ^{35}Ar decay at ISOLDE. In this unique case, a measurement at a 0.5% relative precision would enable to reach a precision on V_{ud} only a factor of ~2 worse than the current best value. There are two experimental approaches for polarizing radioactive nuclei. In the mid-term, it is planned to orient ^{35}Ar ions in a collinear setup, followed by implantation in a crystal. In a longer term, a Magneto-Optical Trap (MOT) will be used to create an ideal polarized ^{35}Ar source.
  - Measurement of the β-ν correlation coefficient *a* in several transitions at LIRAT/DESIR (GANIL). The LPCTrap setup will be upgraded to increase the detection efficiency and to better manage systematic effects. The purpose is to measure *a* at 0.5% in at least four transitions using the new high-intensity beams which should be available at SPIRAL in 2017 (^{21}Na, ^{23}Mg, ^{33}Cl and ^{37}K). This set of experiments will be completed by further $T_{1/2}$, *BR* and *M* measurements.

Theoretical efforts will also be required to compute radiative and ISB corrections. Various theoretical approaches exist which do not yet provide consistent δ_c values. They need to be studied thoroughly, especially on the basis of specific measurements.

Nucleon and nuclear properties from low-energy measurements

Muonic hydrogen and the proton charge radius

The measurement of the proton charge radius by means of laser spectroscopy of the exotic muonic hydrogen atom has yielded a value that is an order of magnitude more precise than the current world average from elastic electron scattering and hydrogen spectroscopy. Surprisingly, the value from muonic hydrogen is 4%, or seven standard deviations, smaller than the value from electronic measurements (see Figure 4). The proton radius discrepancy has created vivid discussions concerning the accuracies of the charge radius extracted from elastic electron scattering and hydrogen spectroscopy, related to the Rydberg constant. Assuming correctness of the experimental results, no possible explanation within the SM exists. Models of physics beyond the SM have been put forward but none of these has been accepted. Recently, the Lamb shift in muonic deuterium has revealed a deuteron charge radius that is also seven standard deviations smaller than the world average from electronic measurements (see Figure 4). The two radii from the muonic atoms are consistent with each other. Many new experiments have been triggered by the proton-radius discrepancy: Improved electron-proton scattering experiments at lowest Q^2, simultaneous measurement of electron and muon scattering on hydrogen for both lepton polarities, improved precision spectroscopy of several transitions in H, D, and He^+, and new measurements in muonic atoms. Several projects aim at a measurement of the ground-state HFS in muonic hydrogen and muonic ^{3}He for a determination of the Zemach radii, a convolution of electric and magnetic form factors. The muonic values can be an order of magnitude more precise than the extraction of those quantities from electron scattering and from spectroscopy of electronic atoms.

Nucleon and nuclear polarizabilities

Uncertainties in nucleon and nuclear polarizabilities limit the accuracy of the charge and Zemach-radius determinations from muonic atoms. The polarizability contributions have to be calculated either from first principles using for example chiral Perturbation Theory, or from

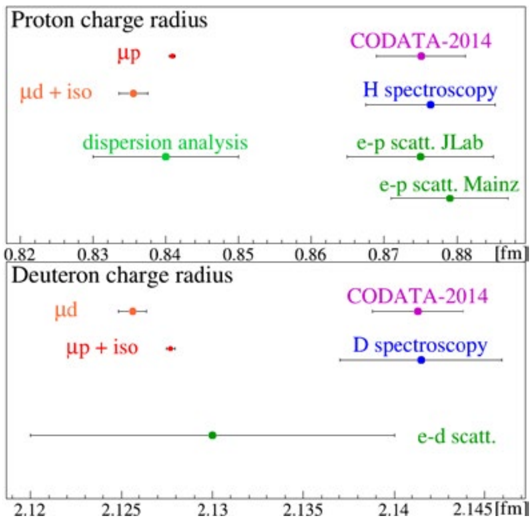


Figure 4: The rms charge radii of proton (top) and deuteron (bottom) as determined by different methods (elastic electron scattering, electronic and muonic H and D spectroscopy, combination of the optical isotope shift measurement with muonic atom results) indicating the discrepancy between the muonic-atom and the electronic results. Also shown are analyses of electron scattering data using dispersion relations, and the CODATA world average.

measured inelastic Compton-scattering data using dispersion relations (see section WG1 'Hadron Structure). Alternatively, the polarizability can be determined from the muonic measurements, provided that accurate charge radii are known, for example, from electronic isotope-shift measurements. The measured Lamb shifts in muonic hydrogen and deuterium, combined with the electronic H/D isotope shift, presently yield a three times more precise value for the muonic-deuterium polarizability correction than the one achieved with state-of-the-art EFT calculations. In the chain of helium nuclei, the isotope shifts of (electronic) ^{3,6,8}He have been measured relative to the ^{4}He reference nucleus. A recently completed experiment in muonic ^{3}He and ^{4}He will check these isotope-shift measurements, improve the precision in the determination of the absolute charge radii of all helium nuclei by up to a factor of 10, and yield improved values for the nuclear polarizability corrections. Similar improvements can be expected for laser spectroscopy of muonic lithium, beryllium and boron. Of importance will be measurements with tritium atoms, because ^{3}H is the mirror nucleus of ^{3}He. The 1S-2S transition in electronic tritium yields the nuclear charge radius. With this radius, the 2S-2P Lamb-shift measurement in muonic tritium yields the polarizability. A comparison of the electromagnetic properties of the mirror nuclei ^{3}H and ^{3}He would be a unique possibility to improve our understanding of nuclear forces. Another improvement due to muonic-hydrogen spectroscopy can be expected in one of the oldest QED tests, namely the HFS in electronic hydrogen. This famous 21 cm line has been measured to six parts in 10^{13} in the 1970s already, but the theoretical prediction is limited to the 10^{-6} level because the proton spin-dependent polarizability contribution is poorly understood. A tenfold improvement may seem possible with the measurement of the muonic-hydrogen HFS and investigation of the corresponding proton-polarizability correction.

Combining muonic-atom spectroscopy with elastic electron scattering

The charge radius of a nucleus appears as the slope of the electric form factor (FF) measured in elastic electron scattering (see section WG1 'Hadron Struture). Once the proton-radius discrepancy is resolved, one can gain new insights into the structure of the nucleon when one fixes the slope of the electric form factor, i.e. the Q^2 term of $G_E(Q^2)$, to the precise value obtained from the charge radii measured in muonic-atom spectroscopy. This will yield more precise values for the Q^4 term of G_E, the Q^6 term, etc.

Similarly, the Zemach radii can be calculated from the measured electric and magnetic form factors, G_E and G_M, respectively. The Zemach radii can also be determined from measurements of the HFS in muonic atoms. Thus, such a muonic HFS should improve the magnetic FF similar to the impact of the charge radius on the electric FF. In addition, polarizabilities determined from a combination of muonic- and electronic-atom spectroscopy can serve as further stringent constraints on nuclear two-photon physics derived from Compton-scattering data.

Heavy muonic atoms

Charge radii of medium-to-high-Z nuclei have been measured since long by means of muonic-atom x-ray spectroscopy. The availability of negative muons with very low kinetic energies will allow extending such measurements to radioactive nuclei for which only minute quantities of a few micrograms can be used. Such projects are being pursued at J-PARC and at PSI.

Kaonic atoms

Precision measurements of kaonic atoms, where a negatively charged kaon replaces an electron in a highly excited orbit, followed by de-excitiation and detection of the emitted radiation, will be performed at the DAΦNE Collider at LNF-INFN and at J-PARC. These measurements allow to determine the antikaon-nucleon isospin dependent scattering lengths which are relevant for the understanding of low-energy QCD in the non-perturbative regime (see section WG1 'Hadronic Interactions'), crucial to comprehend the chiral-symmetry-breaking mechanism giving mass to the baryonic matter in the Universe. These studies also help to tune the neutron stars' equation of state connected to the characteristics of gravitational waves emitted by binary neutron-star systems, which are expected to soon be measured by interferometric gravitational antennae. Kaonic deuterium will be measured by SIDDHARTA-2 for the first time in the coming years. By using new types of detectors, such as Transition Edge Sensors, other types of kaonic atoms, including kaonic helium-3 and 4 (transitions to the 2p and 1s level) and kaonic nitrogen will also be measured to high precision. These measurements will allow extracting the mass of the negatively charged kaon with a precision of a few keV, solving a long-standing puzzle involving this fundamental quantity. Laser spectroscopy of exotic atoms beyond positronium and muonium was pioneered with antiprotonic helium at CERN and with muons at PSI. A project aiming at laser spectroscopy of pionic helium is under way at PSI. Feasibility of laser spectroscopy of kaonic atoms will be explored for the first time, which may allow further improvements in the precision of these types of measurements.

Precision nuclear spectroscopy of ^{229}Th

The nuclear level structure of ^{229}Th shows a unique low-energy isomer state, only 7.8(5) eV above the ground state, corresponding to an excitation wavelength of about 160 nm in the ultraviolet range. ^{229}Th is so far the only known isotope with the potential to drive a nuclear transition with (laser) light, bridging the gap between nuclear and atomic physics. In particular, techniques from high-precision spectroscopy and quantum optics can be transferred to the nucleus. The expected long lifetime and a corresponding narrow linewidth, plus the intrinsic robustness of nuclear quantum states against external perturbations, make this system an excellent candidate for a new time standard with the potential to outperform current optical atomic clocks and to reach 10^{-19} precision. The exact isomer energy and hence the transition frequency is determined by the nuclear energy scales involving the weak, the strong, and the electromagnetic forces. Reaching atomic-spectroscopy precision in this nuclear transition increases the sensitivity to temporal variations of fundamental constants by many orders of magnitudes. Optically driving the thorium transition would become the primer for a new emerging field of nuclear quantum optics and metrology.

The weak charge of the proton

A new measurement of the weak charge at a low momentum transfer of Q^2=0.0049 (GeV/c)^2 aims at extracting the weak mixing angle $\sin^2\Theta_W$ with a 6 times improved accuracy as compared to present low energy values from atomic physics at the new MESA accelerator in Mainz (P2). The JLab Hall C experiment Qweak has finished data taking in spring 2012 and a factor 3 improvement over the present accuracy is expected from the analysis of the full data set. A measurement of the weak charge of the electron with the future MOLLER Experiment at JLab (Moeller-scattering) as well as a measurement of the weak charge of the u,d-quarks (deep inelastic scattering, SoLID) will allow for a complimentary extraction of the weak mixing angle. The mass range for BSM-physics in a four fermion contact interaction ranges from 22 TeV (SoLID), 33 TeV (Qweak), 39 TeV (MOLLER) up to 49 TeV (P2).

SEARCHES BEYOND THE SM

Fundamental-symmetry tests

Testing fundamental symmetries and related conservation laws is a prime route toward establishing the limits of the SM. Experiments at low energies can be particularly sensitive due to the availability of well defined systems, of high-precision spectroscopy methods and of high particle intensities. Test of symmetry violations comprise those of the fundamental discrete symmetries of parity (*P*), time reversal (*T*), charge conjugation (*C*) and their combinations *CP* and *CPT*. Searches for *CP* and *T* violation beyond that found in meson physics are greatly motivated by the observed BAU and also by the natural appearance of *CP* violating phases in extensions of the SM. The search for *T* violation with EDM and weak decays and measurements of *P* violation in atomic and molecular systems are especially powerful. A similar motivation fuels searches for *L* and *B* violations which might help understanding BAU. Such violations may have a close connection to the unknowns of neutrino physics, to Grand Unification and in general to the beyond SM physics as parametrized for instance in the SMEFT. We emphasize here the importance of the *L* violating $0\nu\beta\beta$ decay searches, the most sensitive cLFV decays of muons, and, besides the search for the ΔB=1 violating proton decay with large-mass neutrino detectors, the discovery potential of a new search for the ΔB=2 violating oscillation of neutrons to antineutrons.

Searches for *CP* and *T* violation

Permanent electric dipole moments (EDMs) violate both *P* and *T* symmetry. They offer a promising route for exploring additional sources of *CP* violation and to explain the matter-antimatter asymmetry. The discovery potential of searches for EDMs has led to a number of experiments on different systems. There are searches for the neutron EDM with the promise of 1-2 orders of magnitude improved sensitivities compared to the present limit of $d_n < 3.0 \cdot 10^{-26}$ e·cm (90% C.L.). In Europe these efforts rely on improved neutron sources at PSI, ILL and at the future ESS. Experiments with atoms, molecules, and ions exploit large enhancement factors in composite systems. Such enhancements can be up to of order 10^6 for the electron EDM in heteronuclear molecules. This enabled a strong recent limit on the electron EDM $d_e < 1.1 \cdot 10^{-28}$ e·cm (95% C.L.) using ThO molecules. Such an approach can be expected to deliver more stringent limits due to improved experimental techniques for a variety of molecular systems (YbF, ThO, BaF, HfF^+). The combination of large EDM enhancement factors and extended coherence and observation times in beams of slow molecules will further significantly improve the sensitivity to d_e.

A theoretical framework is required to disentangle hypothetical sources for CP-violation. Composite systems are sensitive to various *CP* violating sources and the ThO EDM experiment presently also sets the most stringent bound on *CP* violating electron nucleon couplings. The tightest bound on a nuclear EDM arises from an atomic ^{199}Hg experiment, $d_{Hg} < 7.4 \cdot 10^{-30}$ e·cm (95% C.L.), which constrains various *CP* violating effects involving gluons, quarks, nucleons and electrons.

Improvement in shielding and compensation of magnetic fields and gradients is essential for increasing the sensitivity of current experiments. Similar to the neutron EDM search where a co-located ^{199}Hg magnetometer allowed for major progress, gas mixtures of hyperpolarized ^{3}He and ^{129}Xe are exploited to search for the EDM of ^{129}Xe with ^{3}He as co-magnetometer. Here coherence times of several thousand seconds and large numbers of particles offer a potential improvement of up to four orders of magnitude over a previous bound in ^{129}Xe, which is approximately equivalent to an improvement of two orders of magnitude over the present ^{199}Hg results.

Another approach towards measuring EDMs employs light charged particles or nuclei in electric and/or magnetic storage rings. In such an experiment, an EDM could manifest itself as an out of orbit-plane precession of the particle spin. Here the rather high motional electric field which a stored particle experiences when it moves in the storage ring is exploited. The experiments, in Europe for the proton and the deuteron within the JEDI collaboration, are in development stages concerning equipment and principal experimental techniques. As a proof-of-principle, the last g_μ-2 storage-ring experiment delivered a direct limit on the muon EDM $d_\mu < 1.8 \times 10^{-19}$ e·cm (95% C.L.).

Complementary to the search for permanent EDMs is the measurement of triple correlations in nuclear and neutron β decays. Among these correlation parameters, *D* appears particularly interesting:

$$D \propto Im\{|M_F||M_{GT}|C_V C_A^*\}$$

where M_F (M_{GT}) is the Fermi (Gamow-Teller) nuclear matrix element, C_V and C_A are the vector and axial-vector coupling constants, respectively. The *CP* (or equivalently *T*) violation contribution in *D* would thus come from a phase between vector and axial-vector couplings, and its measurement makes sense only in mirror transitions of oriented nuclei. In this case, the required detection setup is another configuration of the setup used for $a_{\beta\nu}$ measurements. Collinear laser spectroscopy systems are suited for the polarization of nuclei like ^{23}Mg and ^{39}Ca which decay through mirror transitions. The degree of polarization expected with ions confined in traps is close to 99%. The measurement of *D* in mirror decays employing traps is therefore an interesting opportunity in the future to lower the uncertainties below 10^{-4}.

Significant efforts on theoretical approaches are also essential to guide development of specific experiments and explore possible interpretations of results from different sources (EDM, *D*) with minimal model dependences. Here, the SMEFT offers great insights.

Another *T* violating observable is studied by TRIC (Time Reversal Invariance at COSY) at FZJ which aims at improving the sensitivity to time reversal at least by one order of magnitude. The total cross section for the interaction of protons and deuterons with both species polarized will be extracted from the measurement of the lifetime of the coasting COSY beam for two spin-orientation scenarios equivalent to time reversal.

P violation in atoms, ions and molecules

The electroweak unification in the SM predicts observable contributions from the weak interactions in atomic and molecular spectra. Here the strength of the weak interactions, i.e. the nuclear spin independent weak charge, and the weak induced nuclear moments, such as the anapole moment, are investigated. The best quantitative measurement of weak effects in atoms comes from Cs and has generated detailed theoretical studies of atomic parity violation. Progress achieved by improved atomic and molecular theory together with experimental techniques lead to a selection of most sensitive systems.

Heavy diatomic molecular systems and heavy elements, e.g. ytterbium and dysprosium, are considered promising choices for measurements of nuclear anapole moments. Advances in slowing, cooling and trapping of molecules together with an enhanced intrinsic sensitivity due to the abundance of near degenerate states enable quantitative measurements of the weak interaction in nuclear matter. Other approaches to measure parity-violation effects include precision studies of selected transitions in chiral molecules and detecting subtle effects in nuclear magnetic-resonance experiments. The spin independent contribution is strongly enhanced in heavy atomic systems (stronger than Z^3). The best quantitative treatment of these many-electron systems is achieved in single-valence-electron systems such as alkali atoms and alkaline-earth ions. Several experiments are under way on radioactive francium isotopes which can be produced in sufficient quantities and confined in atom traps. The alkaline-earth ions Ba^+ and Ra^+ are currently employed in experiments aiming at a fivefold improvement in the determination of the weak-interaction parameters of the SM. Such precise determinations may also be sensitive to extensions of the SM which introduce additional heavy bosons, e.g. Z′ or light dark matter Z_{dark}.

Searches for CPT and Lorentz violation

A direct sensitive test of *CPT* invariance is to measure properties like masses and *g*-factors for both particles and anti-particles. The masses of the neutral kaon and antikaon presently provide the most precise comparison, with a relative difference at the level of 10^{-18}. Figure 5 shows the accuracy reached in various *CPT*-invariance tests. The charge-to-mass ratio of the proton and antiproton was compared at LEAR and at AD (both at CERN) via measuring cyclotron frequencies in a Penning trap. The difference was found to be less than 10^{-10}. A similarly stringent *CPT* test is possible by comparing the magnetic moments of the proton and antiproton stored in a Penning trap. First precision measurements at the level of 10^{-6} have been carried out recently by ATRAP and BASE. Further orders-of-magnitude improvements are expected in the coming years. At present, the only facility to perform such experiments is the AD, constructed in 1999 in order to test *CPT* invariance with antiprotons and antihydrogen. The AD experiments

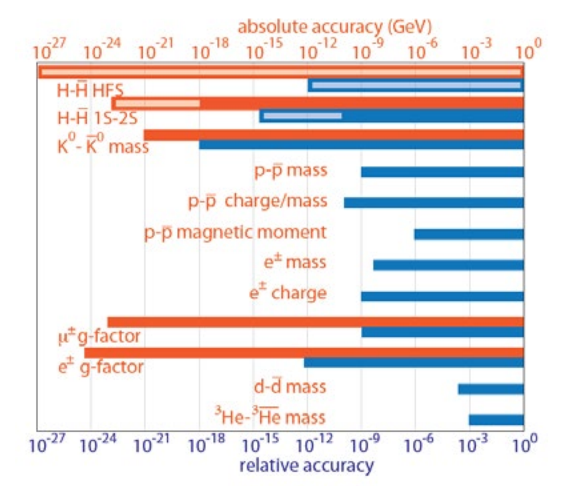


Figure 5: Comparison of several CPT tests in terms of relative accuracy (blue) and absolute accuracy (red) based on the SME model. Values for hydrogen–antihydrogen comparison assume that antihydrogen will be measured to the accuracy that has been achieved for hydrogen.

ALPHA and ATRAP have produced and confined antihydrogen atoms. ALPHA carried out first microwave spectroscopy and 1S-2S laser spectroscopy of antihydrogen trapped in a Ioffe-Pritchard trap. An upper limit on the charge of antihydrogen was established, from which, in combination with upper limits on differences between proton and antiproton, a CPT test at the 10^{-9} level for the relative differences of the electron and positron charges and masses is derived. The ASACUSA collaboration has produced and studied antiprotonic helium. In combination with the Penning-trap measurements, the mass, charge, and (at a lower precision) magnetic moment of the antiprotons was extracted providing a sensitive test of *CPT*. More recent approaches to produce an atomic beam of antihydrogen, a technique also pursued by AEGIS, open up further spectroscopic opportunities. To accommodate the expanding community including GBAR, a further deceleration stage, the ELENA storage ring, has been built and is undergoing commissioning. Possibilities for the longer-term future are provided by the FAIR facility at GSI.

While *CPT*-violation searches involve antimatter probes, *CPT* violation is often related to Lorentz invariance (LI) violation. LI is a corner stone of modern Quantum Field Theories and as such should be tested experimentally. A popular framework in which LI tests are often analyzed is called Standard Model Extension (SME) not to be confused with the SMEFT. The SME includes the SM, but also gravity, and allows intercomparison of different LI tests as the observables can be expressed via the theory parameters. In general, many time stamped precision experiments can be analyzed to constrain the SME parameters. Some experiments test isotropy of space, for example, by comparing the velocity of light in different directions or comparing precession of spin clocks (such as neutrons or ^{3}He) around different axes. While particularly stringent tests were performed in the electromagnetic-interaction sector, weak interactions and higher-generation particle observables have moved into focus more recently.

Spin-statistics tests

The concept of *identical particles* is unique to quantum physics. In contrast to, for example, identical twins or the so-called "standard-candle" supernovae, all electrons, helium atoms, ^{85}Rb nuclei, etc., are, as far as we can tell, *truly* identical to each other. This means that if we have a wavefunction representing a system containing identical particles, particle densities should not change upon interchange of two of these. As a consequence, the wave function should either remain invariant or change sign under permutation of identical particles. This is the essence of the permutation-symmetry postulate (PSP). The spin-statistics theorem (SST) relates, one might argue, a-priori unexpectedly, which of the two options is realized, to the intrinsic spin of the particles. The resulting division of particles into fermions and bosons is one of the true cornerstones of modern physics. SST is proved in the framework of relativistic field theory using the assumptions of causality and Lorentz invariance in 3 + 1 spacetime dimensions, along with a number of subtler implicit assumptions. While it is difficult to build a consistent relativistic theory incorporating SST and PSP violations, it is important to put these properties to rigorous tests given their fundamental importance in our understanding of nature. One may think of such a test as probing all the assumptions in the SST proof, as well as a possible experimental window into theories that go beyond the conventional field theory, for instance, string theory. Since all our observations so far are consistent with PSP and SST, the experiments should search for *small* violations of PSP and SST.

Molecular spectroscopy has played an important historical role in establishing the experimental basis for PSP and SST. The general idea is that in a molecule containing two identical nuclei and assuming, for example, a symmetric electron-spin state, rotational states corresponding to the overall molecular wavefunction being symmetric (in the case of half-integer-spin nuclei) or antisymmetric (in the case of integer-spin nuclei) are forbidden by quantum statistics, and so the lines involving these molecular states are absent from the molecular spectrum. A powerful experimental methodology for testing for statistics violations is to look for such forbidden lines. Recent experiments using $^{12}C^{16}O_2$ molecules containing two bosonic oxygen nuclei limited the relative probability for the molecule to be in a wrong-symmetry state at a $<3.8 \cdot 10^{-12}$ level. An interesting extension is to molecules containing more than two identical nuclei that would allow to probe for more complex permutation symmetries than are allowed for just two identical particles. Another recent experiment using two-photon optical transitions in barium limited the probability of two photons being in a wrong-symmetry (i.e., fermionic) state at less than a part in $4 \cdot 10^{11}$.

Other experiments check for forbidden atomic or nuclear transitions. A particular consequence of the SST is the Pauli Exclusion Principle (PEP), permitting only two electrons in a given state, for instance, the 1s ground state of copper. A limit on the probability for an additional electron in copper to form a mixed-symmetry state constraining PEP violation at the level of $<4.7 \cdot 10^{-29}$ was set by the VIP experiment at LNGS. The successor VIP2 aims to improve the sensitivity by two orders of magnitude.

Similar to SST tests, also rigorous tests of quantum mechanics investigate foundations of our theoretical understanding of Nature. Experiments testing quantum mechanics and its possible limits use various systems, such as elementary particles, photons, neutrons, nuclei, atoms, and molecules. Also these tests will continue in the coming years with ever increasing sensitivity, while having a broader positive impact on quantum technologies.

Search for cLFV

The violation of lepton number is directly searched for in $0\nu\beta\beta$ experiments (see above). Lepton-flavour violation is, in fact, established in neutrino oscillation. With a large suppression, this also induces cLFV. However, a strong motivation for much enhanced cLFV comes from beyond-the SM models which do not explicitly suppress it by additional assumptions. cLFV searches in muon decays have a long history and so far only set upper limits, see Figure 6. The most stringent limit on any forbidden or rare decay comes from the MEG experiment at PSI: $BR(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$ (90% C.L.). International collaborations aim at considerable improvements of sensitivity of their search experiments, MEG II at PSI aims at $5 \cdot 10^{-14}$, Mu2e at FNAL and COMET at J-PARC search for the conversion of negative muons $\mu \to e$ bound to nuclei aiming at 10^{-16} and the Mu3e at PSI will search for neutrinoless $\mu \to eee$ decays in two steps pushing to 10^{-15} and 10^{-16}, respectively. All these experiments

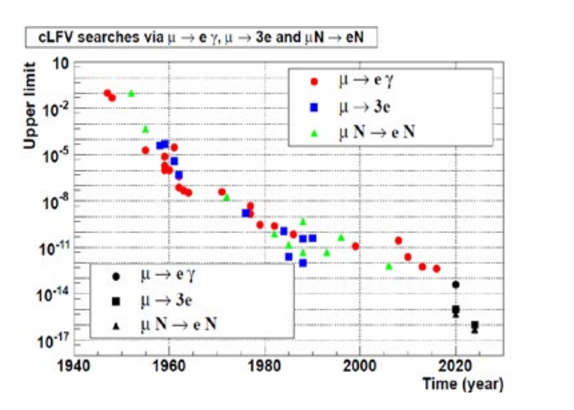


Figure 6: Upper limits (90% C.L.) on decay branching ratios obtained in the searches for muonic cLFV over the years (color symbols). The latest μ→eγ limit ($4.2 \cdot 10^{-13}$) represents the most sensitive of any rare decay search so far. Various projects aim at improving one of these three 'golden' channels (projected sensitivity limits: black symbols).

need high-intensity muon beams with different characteristics, pulsed ones at FNAL and J-PARC and continuous beams at PSI. Recently, options to also probe some more exotic cLFV channels at higher sensitivities are receiving renewed interest. Efforts to search for muonium to antimuonium oscillations can be seen in a similar context as neutron to antineutron oscillations.

Dark Matter, Dark Energy and exotic forces

Cosmology has reached an unprecedented level of precision with the standard cosmological (so-called ΛCDM) model fitting very well all the vast amount of presently available observational data. This standard model of cosmology describes our present Universe and its evolution starting from the Big Bang. However, for the good agreement between data and the model, 95% of the energy content of today's universe needs to be assigned to yet unknown kinds of matter and energy, whereas less than 5% is attributed to normal matter consisting of atomic nuclei and electrons.

Gravitational effects on all scales from galactic (rotation curves) to cosmological ones suggest exotic "Dark Matter" outbalancing normal matter by a factor of five. An alternative approach, modifying the laws of gravity (MOND: modified Newtonian dynamics) runs into difficulties explaining the observations on all those scales. The accelerated expansion of the Universe is attributed to "Dark Energy" contributing about 70% of its energy content.

What is the origin of this "Dark Sector"? It is likely that Dark Matter consists of a new kind of exotic massive particle interacting only "weakly" in addition to gravitationally. Here "weakly" does not necessarily mean the interaction via Z and W bosons. Particle physics beyond the SM provides possible Dark-Matter candidates on a stunningly wide mass scale (see Figure 7), among which the following three are most favored today: weakly interacting massive particles (WIMPs), sterile neutrinos with keV masses (Warm Dark Matter), and axions and axion-like particles (ALPs). The formation of the large-scale structure of today's Universe requires that the dark-matter particles were non-relativistic at structure formation ("Cold" or "Warm" Dark Matter).

Regarding today's accelerated expansion of the Universe, while it could be explained just by a non-zero value of the cosmological constant Λ of Einstein's general relativity, from the particle-physics perspective, it would be natural to associate the accelerated expansion with a new light scalar field.

Many models which introduce new Dark-Sector particles also allow for their, usually feeble, interactions with ordinary matter. Therefore, low-energy precision experiments can test such models searching for deviations in the interaction of particles from their expected SM or standard-gravity behavior. One example is the search for ALPs via exotic spin-dependent forces. As another example, some theories of Dark Matter and Dark Energy predict deviations from the Newton's inverse square law of gravitation at short distances, which has been tested down to 20 μm.

A gravitational quantum theory in the elementary-particle domain has not been established yet. Evaporation of black holes suggests quantum effects of gravitation, but a complete theory does not as yet exist. Therefore, we are still at the stage of collecting empirical data on possible options of gravitational interactions. While gravitational matter-matter interaction has been shown to be universal for macroscopic test masses at a level of a part in 10^{12} and to high precision also for free-falling atoms and neutrons, a direct test of the universality of free fall is still missing for antimatter. Deviations from the known interactions would show up as exotic forces and would most likely be connected to yet unknown particles.

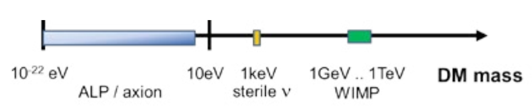


Figure 7: The masses of viable Dark Matter candidate particles span an extremely wide range. Only some of the present candidate particles are displayed.

Direct Search for Dark Matter Particles

Complementary to indirect searches for Dark Matter by looking for products of Dark Matter self-annihilation with neutrino, gamma and charged-particle telescopes, to production of Dark-Matter particles at LHC, and to the search for solar axions with helioscopes, are direct searches for Dark-Matter particles in the Milky Way. A detection of such particles would be a reliable proof of the existence of exotic Dark Matter in our galaxy.

Theories beyond the SM provide plausible Cold Dark Matter candidates. Especially in supersymmetric extensions of the SM (SUSY), WIMPs with masses of several tens of GeV to TeV would have been produced naturally in the right amount in the early Universe. Ultra-sensitive experiments in underground laboratories, for example, dual-phase xenon or argon time-projection chambers like LUX, XENON1T, and DarkSide, are looking for the scattering of WIMPs off nuclei. They have reached sensitivities to WIMP-nucleon elastic scattering cross sections of 10^{-45} cm^2 and below. An improvement in sensitivity by another 2-3 orders of magnitude is expected with these techniques by increasing detector masses and lowering backgrounds within the next decade. Examples of such experiments are XENONnT, DarkSide-20k, ArDM and DARWIN in Europe. Cryogenic bolometers, for example CRESST and EDELWEISS, complement these searches for WIMPs with masses down to the GeV range.

Although the structure formation in the Universe and direct neutrino mass limits exclude the possibility that normal neutrinos make up a large fraction of Dark Matter, sterile neutrinos with keV masses are an interesting alternative for Warm Dark Matter. They can be searched for with direct neutrino-mass experiments or by looking for their decay into standard neutrinos and photons with x-ray telescopes.

Finally, axions and axion-like particles are interesting candidates for Dark Matter. The axion, a hypothetical elementary particle arises in the Peccei-Quinn theory and resolves the problem of non-observation of *CP*-violation in strong interactions that would manifest itself, for instance, as neutron EDM. Strong *CP* violation naturally appears in Quantum Chromodynamics and its absence is puzzling without invoking the axion. Experimental, astrophysical, and cosmological limits have been refined and indicate that axions – if they exist – have to be very light with masses in the peV to meV range. Still, they are counted as Cold Dark Matter. They are searched for in laboratory experiments using Primakoff conversion into microwave photons in a strong magnetic field, for example, in the ADMX experiment. Since the Sun rotates with a velocity of 230 km/s around the center of the Milky Way, our laboratories move with respect to the Dark Matter halo with that velocity additionally modulated by the rotation of the earth. This can be used to look with atomic magnetometers, ultracold neutrons and clocks for periodic modulations due to ultralight bosonic particles that could be components of Dark Matter or Dark Energy.

Test of Dark Energy models with precision experiments

Cosmology with Dark Energy caused by light scalar bosons can be made acceptable by invoking a late stage of inflation with the Hubble constant H_0 less or approximately equal to the mass m_Φ of the scalar boson. A chameleon field as a realization of such a scalar field called quintessence may couple to ordinary matter and mediate a long-range force, which would show up in the fifth-force searches or equivalence-principle tests.

Today chameleon fields are strongly constrained by precision experiments. A significant step forward was made by analyzing gravitational quantum states of neutrons bouncing above a flat surface and by neutron-interferometer experiments. In another approach, an atom interferometer allowed to look for changes in the accelerations of caesium atoms near a spherical mass as a source of chameleon fields. These experiments exclude the chameleon theories that could account for Dark Energy with a coupling constant $\beta > 4.3 \cdot 10^4$. Pushing the sensitivity limit to $\beta < 1$ would completely exclude these classes of chameleon theories.

Exotic forces

Beyond-the-SM particles that may constitute the Dark Sector may modify the known interactions and manifest themselves as exotic forces, e.g. the "fifth force" between two masses. In addition, the "new" particles may couple to charges and spins, producing a variety of possible exotic interaction potentials. For a set of generic assumptions for spin-0 or spin-1 bosons, there are 16 independent potentials in the nonrelativistic limit, the simplest of which is the Yukawa-type coupling. The axion can produce such a coupling with the strength $g_s g_p/\hbar c$, where $g_{s,p}$ characterize the scalar and the pseudoscalar interaction, respectively. The most restrictive limit on $g_s g_p/\hbar c$ was derived by combining the laboratory limit on g_s with stellar energy-loss limits on g_p, which is more stringent than laboratory searches alone.

Various kinds of exotic interactions are currently being probed in a plethora of atomic and molecular systems, including comparison of the experimental and theoretical spectra for relatively simple atoms (helium, positronium), precision measurements of the interaction between trapped ions, comparisons of theory and experimental data for spin-dependent intramolecular interactions (for example, in the HD^+ ion where sub-ppb comparison of experiment and theory was recently achieved). While these experiments probe short-range interactions, similar approaches for long-range forces exist. Test laboratory masses and spin-polarized samples are used to "source" exotic fields that can be probed with atomic magnetometers, as well as with devices sensitive to variation of fundamental "constants." The advantage of the laboratory sources is that they can easily be manipulated to modulate the signal.

Possible Yukawa-type generalisations of Newton's gravitational potential can be written as

$$V(r) = -G/r \cdot m_1 \cdot m_2 \cdot (1+\alpha\, e^{-r/\lambda}),$$

where α is a dimensionless strength factor in comparison with Newtonian gravity and λ is the characteristic Yukawa distance over which the corresponding force acts. In the range $\lambda > 20$ μm, the Seattle torsion-pendulum experiments find no deviation from Newtonian physics. An Atomic Force Microscope was used to perform measurements of the Casimir force and deduced constraints on α and λ at micron distances. Free-falling atoms can be used to probe sub-micron forces by interferometry of Bose-Einstein condensates. Another approach is to explore a single particle, for example a neutron falling in the Earth's gravity in conjunction with a massive object, a mirror, from which the neutron bounces off. In addition to probing for the extra bosons as discussed above, searching for deviations from Newton's gravitational law also probes for other kinds of new physics, such as various forms of extra dimensions. Such experiments are performed by the *q*Bounce and GRANIT collaborations. The use of neutrons as test particles bypasses the electromagnetic background induced by van der Waals and Casimir forces and other polarizability effects.

A class of experiments tests the universality of gravity and the equivalence of the gravitational and inertial mass. Indeed, the universality of the acceleration of free fall has been verified at the 10^{-13} level for laboratory bodies, notably Be-Ti, and Be-Al test masses. A phase shift induced by gravity has been measured in matter-wave interferometers operating with laser-cooled ensembles of ^{87}Rb and ^{39}K atoms. The experiments show that there is no difference in free fall between the two ensembles on the 10^{-7} level. Studies with neutrons have so far reached an accuracy of $3{\cdot}10^{-4}$ in confirming that the ratio m_i/m_g is equal to unity.

Equivalence tests with antimatter have included comparisons of gravitational red shift for trapped charged particles and antiparticles, but are currently focusing on antihydrogen, which should be compared to ordinary hydrogen using the most sensitive atom-interferometry and spectroscopic methods. Initial attempts at much lower sensitivity have already begun: the AEGIS, ALPHA and GBAR experiments at the AD facility at CERN aim to measure the gravitational mass of antihydrogen atoms with a precision in the 0.1-10% range. In spite of the initially modest precision, the first direct measurement of a gravitational effect on antimatter will be scientifically relevant and will pave the way for higher-precision studies. These endeavors will benefit in particular from the increased antihydrogen production rates at ELENA. In the longer term, higher sensitivity might be possible via spectroscopic studies of gravitational quantum states if sufficiently cold antihydrogen atoms can be prepared. In addition to antihydrogen, the study of the gravitational interaction of antimatter appears feasible and is pursued in Europe with the purely leptonic positronium and muonium. The latter is dominated in mass by the second generation antimuon. Initially, measurements of the annual red-shift modulation of the 1S-2S transition frequencies could determine the sign of their gravitational interaction. Atom interferometry methods could eventually lead to a precision of 1-10%.

Temporal and spatial variation of fundamental constants

It is now generally accepted that the Universe has undergone a period of rapid inflation in its early stages, during which the laws of physics in the way we normally think about them have also changed. It is thus logical to ask whether the laws of physics encoded in the values of fundamental "constants" may be evolving even after the inflation is over. In fact, the question of stability of the constants goes back to Paul Dirac. As all other basic laws of physics, the usually assumed stability of fundamental constants requires rigorous experimental verification. One way to look for possible variations of constants is observing absorption spectra of quasars, bright broadband light sources that are at "look-back" times from us comparable to the lifetime of the Universe (~10^{10} y). As the light from quasars travels towards us, it undergoes absorption by atoms and molecules in the interstellar media. Once we detect the corresponding absorption lines via astronomical observations, we can correct the spectra for the red shift, and compare them with the spectra recorded in the laboratory. A change in fundamental constants, for instance, the fine-structure constant α is revealed in the difference of the spectral profiles. In fact, by the late 1990s, there appeared evidence that α may have been approximately one part in 10^{10} smaller in the early Universe than it is today. Interestingly, assuming a constant rate of variation, this would mean a fractional variation of α at a ~10^{-15}/y level, not too far from the stability level of the state-of-the-art atomic clocks at that time. This led to a rapid development of laboratory experiments searching for present-day variations of constants.

The current situation is that there is no uncontested spatial or spatio-temporal variation of any of the dimensionless fundamental constants, although the searches are rapidly improving, especially on the laboratory side, where the level at which the variation is being probed is already better than ~ 10^{-17}/y. The above-mentioned possibility to exploit the ^{229}Th nuclear clock transition might allow for further considerable improvements. Moreover, it has been realized that laboratory experiments can be sensitive not only to a monotonic drift of the constants, but also to their oscillating and transient behavior. Such time-dependent effects can be related, for example, to ultralight scalar fields that are part of Dark Matter, and the experiments of this type are opening a completely new window into the study of Dark Matter.

PERSPECTIVES

The research of "Symmetries and Fundamental Interactions" covers a huge range of physics questions which are all aimed at discovering and testing the most basic laws of Nature, Matter and the Universe. Although there has been tremendous progress made since the last Long Range Plan in many research areas, among others by setting new stringent limits e.g. on the unitarity of the CKM quark mixing matrix, the neutrino mixing angles and the validity of quantum electrodynamics in strong fields, there is still the quest for ever more precise tests. To this end the researchers are combining and applying the most sensitive methods of a variety of fields. However, most often the success depends on the available expertise in experiment and theory as well as on the available beamtime, beam intensities and cleanliness of the beam of the particles of interest at the European facilities. Thus, NuPECC's focus should be concentrated on state-of-the-art possibilities to achieve the goals in the field and to pave the way for potentially important discoveries.

In the following, some future directions in the field of "Symmetries and Fundamental Interactions" shall be given:

Electroweak Interaction

The advances in technology and techniques, in particular regarding trapping, lasers, high-precision frequency measurements, detector technology, particle beams and particle manipulation have allowed for considerable progress in the determination of fundamental parameters and quantities like masses, electromagnetic moments, lifetimes and weak decay correlations. They have also opened several windows for further large steps forward, both in technology development and in physics reach. We expect on the one hand improved tests of QED, pushing into a region where they become more and more sensitive to weak, hadronic and nuclear corrections. These will allow testing our understanding of such corrections but also, by clever experiment selection, to cancel them to a large degree and extract fundamental constants. On the other hand, major progress in nuclear and neutron decay experiments will push several weak observables into the sub per mill accuracy region. This will provide unprecedented constraints on possible exotic extensions of the standard weak interaction theory. Precision experiments turn more and more into most powerful search experiments for deviations of the standard theory providing a huge discovery potential.

Neutrinos

Although the still unknown neutrino mass scale is being scrutinized more and more by cosmology the efforts to measure it in laboratory experiments needs to be continued both by direct experiments investigating the kinematics of beta decays or indirectly by the search for neutrinoless double beta decay. Novel concepts in direct neutrino mass experiments may allow to improve the sensitivity below 100 meV in future. Neutrinoless double beta decay searches with ton-scale masses may reach half-life sensitivities of 10^{27} yr and beyond not only probing the neutrino mass to the sub-100 meV level but also lepton number violation and the various beyond the Standard Model scenarios of neutrino mass generation. These experiments need to be accompanied by theory efforts to understand better the nuclear matrix elements of neutrinoless double beta decay. Neutrino oscillation experiments with reactor, accelerator and atmospheric neutrinos will allow to determine the neutrino mass hierarchy within the next decade. The determination of a finite CP-violating phase in the neutrino sector aimed for by accelerator neutrino experiments might complete our understanding of the neutrino mixing matrix. Searches for a fourth or fifth generation of (sterile) neutrinos may provide us new surprises.

Fundamental Symmetries

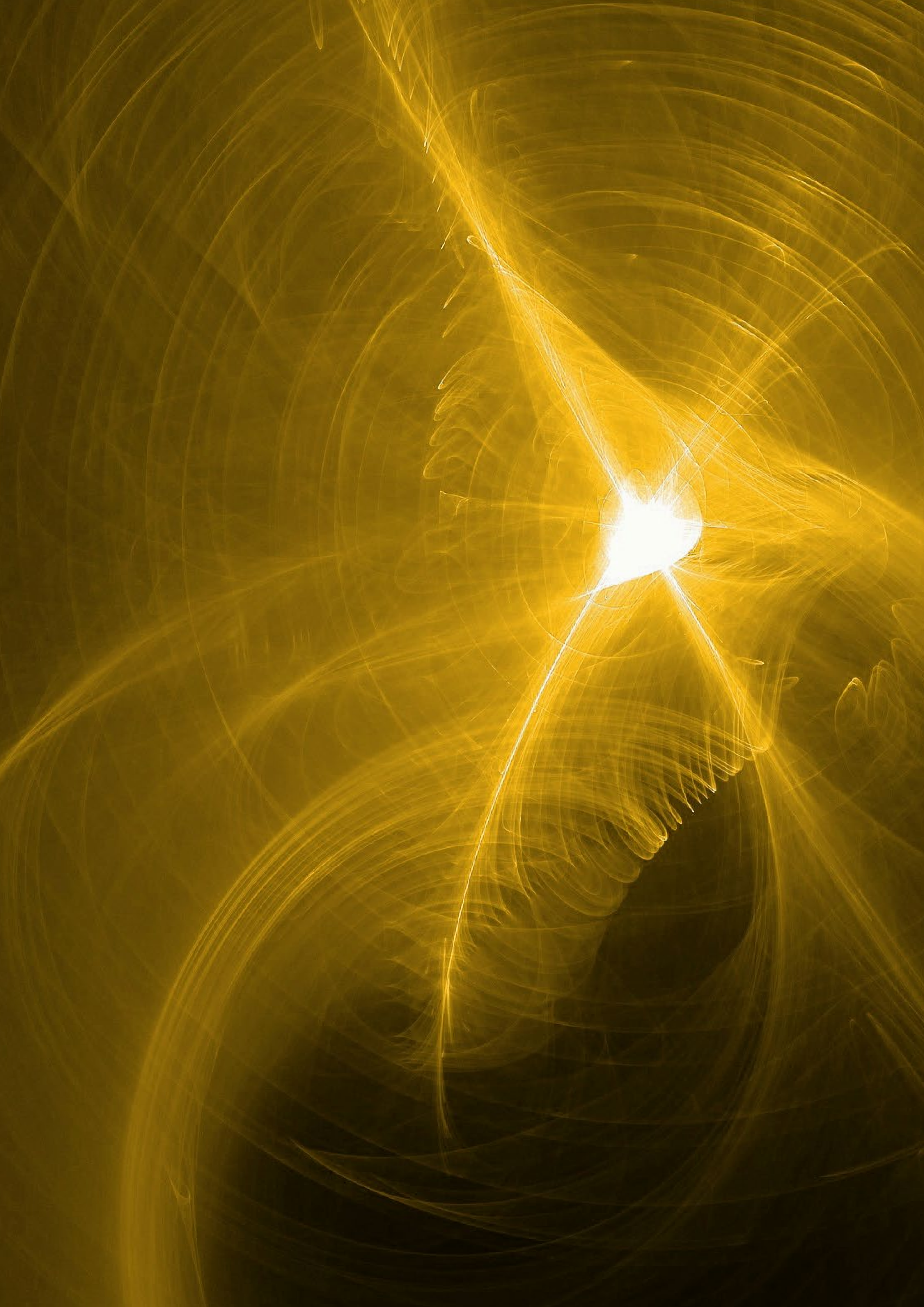
Tests of *C*, *P* and *T*, both individually and in combination, immediately benefit from ongoing advances in experimental techniques, such as improved trapping and cooling of atoms, ions and molecules, or enhanced production rates of specific isotopes or accelerator-produced particles such as neutrons, muons and antiprotons. In parallel, focus is increasingly also shifting to tests of fundamental assumptions (such as the Pauli exclusion principle, lepton number and charged lepton flavor conservation, Lorentz Invariance and others) where a number of experiments are poised to improve sensitivities by several orders of magnitude in the coming few years. Similarly important, experiments will further explore and improve sensitivities to various Dark Matter and Dark signals and provide competitive constraints. Tests of the WEP with antimatter (using antihydrogen, positronium and muonium) underline the importance of a range of complementary approaches to ensure that first rough measurements are obtained already in the near future, while higher precision measurements possibly building on these could easily take a decade.

RECOMMENDATIONS

Mandatory for the achievement of the above listed challenging goals are an appropriate funding and environment including adequate academic positions for young researchers and state-of-the-art facilities. In detail, we recommend the following actions:

- Adequate funding of university groups should be ensured. Many of the precision experiments to study fundamental interactions require dedicated table-top setups in university laboratories where they can either be pursued or where innovative techniques are tested before they get installed at larger online facilities and large-scale infrastructures.
- Trap and beam development: common to almost all experiments in the field of precision tests of fundamental symmetries and their interactions are cooling and storing. To that end, charged as well as neutral particle traps and cold beams need to be improved to extend their applicability, to increase their sensitivity and accuracy as well as to address new observables
- Continued or even stronger support for theoretical research groups, as well as for theorists "embedded" in experimental groups. High-precision measurements of fundamental physical constants, low-energy tests of the Standard Model, and searches for new physics in high-precision spectroscopic measurements require accurate theoretical descriptions of the involved systems, e.g., atomic and molecular states. In addition to the appropriate treatment of QED and weak-interaction effects, one has to account for the influence of nuclear structure which is often a major source of theoretical uncertainties. Moreover, for the comparison of sensitivity of new physics searches at different energy scales it is important to interconnect them by using the same theoretical framework. Most importantly, theoretical guidance and new ideas are indispensable to open up new research fields.
- For the exotic systems to be investigated, dedicated laboratories with intense sources are indispensable. The following facilities are of vital importance for our field and should be continuously supported:
    - The antiproton complex AD/ELENA at CERN, which is a worldwide unique facility for antimatter studies.
    - Cold and ultracold neutrons facilities: these are available at the material science facilities ILL and FRM-II, which also have a strong program in fundamental physics with neutrons. The upcoming ESS is a facility of similar kind, which has a huge potential for fundamental neutron physics which should be realized.
    - Radioactive beam facilities GSI/FAIR, ISOLDE, GANIL, LNL, and JYFL: these key facilities for nuclear physics in Europe provide short-lived radionuclides.
    - GSI/FAIR provides highly charged ions in storage rings for fundamental research.
    - PSI produces the world's highest intensity low-momentum pion and muon beams as well as ultra-cold neutrons.
    - Electron scattering facilities like MESA are important tools to study fundamental properties of the proton, e.g. its radius and weak charge.
    - DAΦNE in Frascati is the only laboratory in the world producing low-energy kaons for exotic atom research.

  - The underground laboratories at Europe's leading institution LNGS as well as at Modane and Canfranc, which house the most background sensitive experiments.
- Upgrades and support of existing small facilities as well as large scale infrastructure in Europe, including underground laboratories and accelerators, should be continued.
- Sufficient access and beam time should be provided, as this is mandatory to push the limits of the present best experiments and to allow for new dedicated setups.
- R&D for new initiatives should be vigorously pursued.



6

APPLICATIONS AND SOCIETAL BENEFITS

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6. APPLICATIONS AND SOCIETAL BENEFITS

INTRODUCTION

The Nuclear Physics community has been and is still able to be mobilized to answer fundamental needs and questions addressed by the society specifically on energy, health and security. This has led to a new transverse discipline of Applied Nuclear Physics research.

Improvements in nuclear applications were obtained thanks to an increase of the basic knowledge on nuclear structure and decay, nuclear reactions and nuclear system properties but also thanks to the developments performed in the related technologies: accelerator, instrumentation and high-performance computing.

Nowadays, it is obvious that society largely benefits from the large investments done in basic Nuclear Physics research. Recent achievements in particle- and radio-therapy within the new paradigm of theranostic approach are some of the most striking examples of the benefits from Nuclear Physics.

Reliable, up-to-date and well-structured nuclear data libraries are indispensable for a whole range of nuclear science applications. Fundamental Nuclear Physics requires also the data to improve knowledge and plan future activities that may lead to new discoveries. The key issue that should be addressed by the European Nuclear Physics community as a whole is how to develop and maintain a high level of expertise in the area of nuclear data to meet the data needs of a continuously developing European nuclear physics landscape.

In this chapter, we try to review the achievements done in this field since the last Long Range Plan in 2010 together with the highlights and open problems. Specific perspectives and needs are formulated in sections. General needs for the future of Applied Nuclear Physics in Europe are summarized by the end.

The chapter is divided according to the different domains of applications:

- Energy
- Health
- Environment and Space
- Society
- Cross-disciplinary impact in other domains

ENERGY APPLICATIONS

Due to the large amount of energy released during a nuclear process, the use of nuclear reactions offers the best energy-density solution to produce energy. Therefore, nuclear reactions are widely used in terrestrial reactors and envisaged in space missions to produce electricity. With a predicted growing of the energy world-demand and the development of carbon emission-free energies in the next decades, nuclear energy could help to reduce the dependence on fossil fuels and their impact on the world global warming. Despite the large amount of work done since the discovery of the fission process and its use for civil energy generation there are still key questions and related key issues that the Nuclear Physics community could contribute to address.

Key questions

- How can advanced nuclear systems help to the sustainability and acceptability of nuclear energy generation?
- How can safety of current nuclear reactors be improved?
- How can nuclear power source be provided for space applications?

Key issues

- Accurate nuclear data and predictive modelling of nuclear processes
- Design and construction of high-power and reliable accelerators and targets.
- Stability of components in extreme environments (radiation and chemically reactive)
- Synergies with other fields (radioisotope production, silicon doping, fuel and material testing, fundamental research)

Next-generation fission reactors

Nuclear fission is an important source of electricity production that will still play an important role in the future. However, the sustainable production of energy using nuclear power relies on improvements in safety standards of current nuclear reactors and, more importantly, on the development of advanced systems, characterized by an optimized use of natural resources, minimized production of radioactive waste to be disposed of in geological repositories, increased safety and reduced proliferation risks, as well as economic competitiveness. Generation IV fast reactors, Accelerator Driven sub-critical Systems (ADS) and new nuclear fuel cycles are some of the most promising options being investigated.

Together with the development of new systems, in the wake of the Fukushima accident it has become of high priority in Europe to improve safety standards of existing nuclear reactors, as well as of fuel fabrication and waste management installations. The performance and safety limits of present and future nuclear power plants should be evaluated not only in standard operation mode, but also under extreme external conditions. The accident in Japan, together with the stress test performed on EU nuclear reactors after the Fukushima event, have posed new challenges on the predictive power of tools and methods currently used for reactor calculations, as well as on the accuracy and reliability of available nuclear data and simulations for systems in extreme conditions.

Nuclear data and models are among the key ingredients for the assessment of the performance of nuclear systems in normal and accidental conditions. Although important progresses have been made in the last few years in this respect, at the European and International level, thanks to new facilities, advanced detection and acquisition systems and improved evaluation methods, the accuracy of nuclear data and reliability of models and simulation tools is still far from satisfactory and large efforts are needed to improve this situation, as demonstrated by the long-standing needs for data in the NEA High Priority Nuclear Data Request List. Among isotopes needing better data are several actinides and fission fragments, particularly those most difficult to measure. When dealing with safety, uncertainties and covariance matrices are needed and should be carefully evaluated within nuclear data and carefully implemented within simulation codes.

It should be emphasized that nuclear data uncertainties are the ultimate limit of the precision

Box 1: Nuclear Data

In absence of predictive and reliable models able to describe nuclear reactions with the accuracy needed to fulfill the requirement imposed by nuclear systems in operation, Nuclear Data are the key ingredients in the simulation codes to assess the performances of innovative nuclear systems in normal and accidental conditions. Indeed, any calculation or simulation of the behavior of a nuclear system, and its safety limits, heavily relies on the production and transport of neutrons, photons, charged particles and recoil nuclei. Improving the accuracy of neutron-induced reaction cross section data for a variety of isotopes and over a wide range of energies is, for example, fundamental for the neutronics of the core and the production of radioactive elements. Similarly, improvements in the accuracy of fission yields and decay data are necessary to calculate the energy deposition inside the fuel element, the decay heat in case of urgent stopping and to predict the evolution and assess the safety of spent nuclear waste. An important part of the activity is related to nuclear data evaluation, with complete uncertainty and covariance analysis needed, as well as compilation and continuous maintenance of the nuclear data libraries as the JEFF European library.

The European Nuclear Physics community can rely on a number of infrastructures and laboratories that can allow for some challenging measurements. This is the case, for example, of the high-flux neutron facilities of ILL, Grenoble, n_ToF at CERN and NFS at GANIL compleneting the well-established EU facilities for nuclear data in the Joint Research Centres (in particular IRMM in Geel, Belgium). Fission yields and decay data can be collected in various laboratories around Europe, such as Lohengrin at ILL, ISOLDE at CERN or the future SPIRAL2 and SPES radioactive ion beam facilities. Finally, experiments at reactor facilities are important to constrain nuclear data evaluation. The key facility for integral data is the VENUS-F reactor at SCK*CEN, which is in 2017 the only operational fast spectrum zero-power reactor in the world. MASURKA in France and BFS in Russia are under reconstruction.

of the simulation systems. Recent developments have made simulation tools more flexible and suitable for a wide range of applications, but the accuracy of the simulation results depends essentially on the predictive power of underlying models and, especially, on the accuracy of the nuclear data they rely on.

Accelerator Driven sub-critical Systems

The production and management of long-term radioactive hazard in nuclear fission reactors is one of the crucial points to be addressed for the public acceptance of this energy production. Accelerator Driven sub-critical Systems (ADS) for nuclear waste transmutation represent the possibility to solve this problem efficiently. The system based on a sub-critical reactor with a spallation neutron source provided by a high-power accelerator with a heavy metal target will be inherently safe. This will be ensured thanks to a robust and accurate online monitoring of the sub-criticality level. However, before the first concept of ADS is realized and its feasibility proven, many challenges should be overcome. The main needs concerns improvement of nuclear data libraries and nuclear reaction models (mainly for neutron-induced as well as for spallation reactions), the development of structural materials able to sustain harsh environment of liquid heavy metal coolant pool, the construction of reliable high intensity accelerators, resilient and save spallation targets and effective minor actinide burning technologies.

In past years, the key ADS spallation target development project was the MegaWatt Pilot Experiment (MEGAPIE) at PSI. After almost 15 years MEGAPIE has reached its final phase – the Post Irradiation Examination (PIE) of the target structural materials and the Lead-Bismuth-Eutectic (LBE). In total the project has undergone ten main phases, from the first idea and design of the spallation target and ancillary systems through the target construction at ATEA, the integral test of the target system behaviour and licensing to its operation in the spallation neutron source SINQ at PSI with the MegaWatt proton beam provided by the High-Intensity Proton Accelerator (HIPA) to the MEGAPIE system dismantling and disposal. The final stage, the Post Irradiation Examinations (PIE), is currently carried out in Hot Laboratories in Belgium, France, Japan, Switzerland and the USA and provides precious information on structural materials and LBE behaviour under irradiation for future spallation sources. Results on the production of radioactive isotopes will help to constrain simulation codes.

In Europe, the key ADS demonstration project is MYRRHA at SCK·CEN. The project started in 1998 and since then the design has evolved into a multi-purpose, large-scale, flexible facility comprising the radioactive ion beam installation ISOL@MYRRHA.

A mock-up of the MYRRHA reactor core was already studied within the GUINEVERE project (2007-2011) and the coupling to a GENEPI-3C accelerator in the FREYA project (2011-2016). The methodologies for online reactivity monitoring of an ADS as well as nuclear data and neutronic codes has been validated (MCNP, Serpent, ERANOS) within these experiments. In experimental campaigns with many various configurations, highly enriched uranium fuel, solid lead as a coolant simulator, various types of reflector materials and thermal spectrum in-pile sections were used. Reactivity effects like coolant void and fuel Doppler effects have been measured. The investigation will continue and extend to instrumentation optimization within the MYRTE project, when the VENUS-F core will be loaded with bismuth and fast spectrum in-pile sections.

Other tasks being performed within the MYRTE project (2015-2019) are the R&D of the MYRRHA accelerator (reliability analysis, injector and superconducting cavities demonstration, beam diagnostics development), as well as the study of thermal hydraulics phenomena in the MYRRHA reactor pool, of the chemistry of volatile radionuclides (polonium and fission products, e.g. I, Te, Ru, Cs) and of the properties of actinide $(U,Am)O_2$ fuel. In the next few years, all this activity is expected to provide important information on the feasibility of the ADS concept and eventually lead to the final design of a transmutation system.

Fusion reactors

Fusion is being considered the holy grail of production of cheap and "clean" energy and enormous progress has been made on plasma confinement on fusion devices during the last decades.

One of the biggest challenges currently being addressed is the construction of the International Thermonuclear Experimental Reactor (ITER) in Cadarache, France. Among the many problems that should be faced is the effect of the extremely high flux of high-energy neutrons on the structural material. The neutron flux in a fusion reactor will have a large impact in limiting the lifetime of various components inside the reactor itself. An accurate study of the damage in the structural reactor materials is necessary. In this respect, the envisaged construction of a test irradiation facility producing neutrons with a broad peak at 14 MeV, like the ones produced in the d-t fusion reaction, is mandatory. In the medium and long term plan the International Fusion Materials Irradiation Facility and/or DEMO-Oriented Neutron Source (IFMIF/DONES) will play a key role in providing fundamental data to assess the level of radiation damage in the various components of the fusion reactors, and estimate their life-time. Such irradiation facilities will also be very useful for testing and validating models and calculations on irradiation effects in fusion power plants, as well as for space research.

At present, however, the effect of neutron irradiation on the various structural components of the future fusion reactors can only be estimated with models, which in turn heavily rely on cross section data. It is therefore important, in the short-medium term, to collect accurate data on neutron-induced reaction on various elements. Apart from producing defects as a result of elastic scattering, neutron induced reactions will be responsible for transmutation of elements in the structural components, activating them and modifying their integrity and stability. Furthermore, neutron reactions leading to charged particle production will be responsible for gas production in the material, which could produce modification of the geometry, for example due to the formation of bumps, as well as of the thermo-mechanical properties, leading to swelling and embrittlement. This is particularly true for (n,α) reactions producing Helium. The list of involved elements is rather long from light to heavy elements: Be, Fe, V, Cr, Mo, Nb, Ta, Zr and W.

To improve models of damage produced by neutron irradiation in fusion reactors, differential and integral data in a wide neutron energy range should be collected, and an accurate database constructed and maintained. Neutron facilities like n_TOF at CERN, NFS at GANIL, and smaller mono-energetic neutron facilities can be exploited in this respect. The optimization of models will at the end rely on the irradiation facilities, but improvements in the nuclear physics input, both in terms of data and theories, on which these models are based, should be pursued with high priority in the next few years.

Nuclear power sources for space applications

Photovoltaic cells are well established as the appropriate primary power source for most space missions. They are a relatively inexpensive, reliable, well established technology. However, they are not practical for future science missions to the outer planets or for missions with planetary Landers or mobile explorers. For deep space missions, the major problem is that the power they generate is inversely proportional to the square of the distance from the Sun. Thus, for an array of a given size, the power it can generate at, say, Jupiter will be less than 4% of the power it generates at the Earth and at Saturn less than 1.5%. Even closer to the Sun the usefulness of photovoltaic arrays on long duration planetary landers and explorers may be limited due to long day/night cycles, atmospheric attenuation and/or dust storms. The nuclear power systems are the only viable alternative to photovoltaic arrays for the long–term production of power in space (see Figure 1).

Space nuclear power systems can be conveniently divided into three categories. In order of increasing complexity, these are:

- Direct production of heat by radioactive decay. Typically, they are low power devices producing between 1 and 10W of heat and are placed directly where heat is required.
- Radioisotope Power Sources (RPS) which generates electrical power by converting the heat released from the nuclear decay of radioisotopes into electrical energy *via* one of many conversion processes. To date, space missions have largely relied on Radioisotope Thermoelectric Generators (RTG), in which the conversion process is mediated by the Seebeck effect using an array of thermocouples, providing a typical power output up to a few hundred Watts electrical.
- Nuclear reactor systems. Power systems

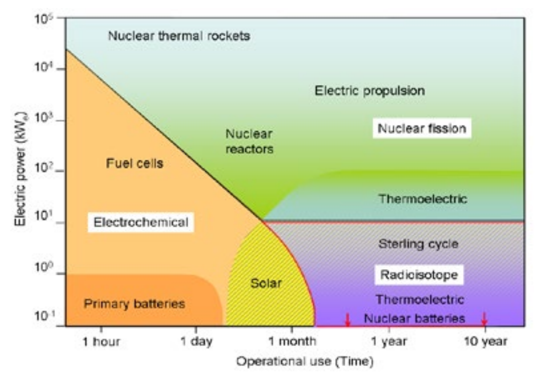


Figure 1: A comparison between nuclear power sources and other forms of space power, which maps the most suitable power technologies for different power level ranges and mission duration. In general, RPS are best suited for applications lasting more than several months and power levels up to one to 10 kilowatts.

based on nuclear fission provide a more cost effective solution than RTG's, if power requirements exceed ~ 1 kW electrical.

Now, research is concentrating in several key areas. In Europe, the major emphasis is on developing new fuel and production technology to replace ^{238}Pu which, as a by-product of nuclear weapons production, is no longer available. Current efforts concentrate on ^{241}Am, extracted from civilian waste stocks. Complementary efforts are also underway in improved electrical energy extraction (up to 100W$_e$) through the development of new, matched thermo-electric materials and efficient and reliable heat engines.

In addition to macro power sources in the range ~10-100 W$_e$, a need for miniaturized nuclear power sources has also recently arisen, largely fuelled by the growing interest in small satellites and technical developments in nano-technology. These extend from 1 watt devices for powering systems and instruments down to milli-watt nuclear batteries for powering nodes in wireless network-based spacecraft. Promising candidates are based on direct energy conversion; so-called alpha and beta-batteries. These utilize active semiconductors to convert the radioactive emissions generated by embedded alpha and beta sources directly into electron-hole pairs and then into usable power *via* a resistive load.

Lastly, although there has been continual interest in nuclear propulsion, its realization must be considered very long term, in view of the current low technology readiness levels, coupled with perceived safety issues and the continued lack of significant funding.

Perspectives and needs

Addressing the challenging needs posed by the Fukushima accident and by the subsequent policy shift towards reactor safety will be one of the main priorities for the next several years for the Nuclear Physics community of experimentalists, theoreticians and evaluators involved in energy applications.

Together with new measurements, the development of predictive and reliable models and simulation tools is mandatory for nuclear energy systems. Since regulators and operators rely significantly on modelling and simulation for safety assessment and licensing, it is of outmost important for the Nuclear Physics community to devote a large effort to refine modelling, simulations and other predictive methods, so that they can provide reliable predictions both in standard and extreme conditions. This can be done only by a strong cooperation between experimentalist, theoretician and evaluators. Considering the large effort required on the evaluation process, it is important that a continuous support be ensured to the evaluation community, at present rather weak, with fresh new forces needed all over Europe. In this respect, the training of a new generation of young researchers is becoming mandatory.

The European research funding programs bring together the majority of European neutron sources. The projects ERINDA, CHANDA, ANDES, etc., help to prepare the methodologies, facilities, detectors, interpretation and tools to produce and use nuclear data with very high quality. Such intensive cooperation is the main reason of significant improvement of the experimental (EXFOR) and evaluated (ENDF) databases and the TALYS code during last years. It will be important to use the Horizon 2020 program in the same way.

In the next years, it is of paramount importance to maintain and optimize the use of available European nuclear data facilities and maintain and support smaller facilities for specific needs, such as for example detector tests and training of young researchers. It is also important to facilitate the access and integration of experimental teams, which are normally multinational, and support the development of innovative methodologies and instrumentations.

Nuclear Physics thus remains a significant player in the worldwide effort for sustainable, safe and acceptable future power generation based on the nuclear processes. For that particularly:

- Efforts in nuclear data measurements, evaluation and modelling are needed and should be supported
- Development for high power and high stability particle accelerators should continue.
- A high level of competence in applied nuclear physic through training and education of young researchers must be maintained.
- Synergies with other fields (detectors, accelerators, materials science, ...) should be exploited
- Specific European projects as MYRRHA and IFMIF/DONES should be supported

HEALTH APPLICATIONS

Ionizing particles strongly damage the DNA of tissue cells, ultimately causing their death. Cancerous cells are particularly vulnerable to ionizing particles because of their reduced ability to repair damaged DNA. This property is used since many years for cancer treatment. Different techniques are developed using external accelerated charged particles, X- or gamma-rays or internal radioactive decaying nuclei. In parallel imaging techniques using radiation properties are also developed to improve the diagnostics and the efficiency of the treatment. The Nuclear Physics community is mobilized to improve the existing techniques and developed new ones to address the key questions and related key issues in this field.

Key questions:

- How cancer treatment efficiency can be improved, reducing the dose to the patient?
- How diagnostic methods can be improved?
- What are the risks of low-dose radiations?

Key issues:

- To develop new methods to better target the treatment on the tumour cell.
- To improve imaging technologies for better diagnostics and reduced dose to patients.
- To develop radiobiology studies.

Particle therapy

Charged particle therapy has been largely driven and influenced by nuclear physics. The increase in energy deposition density along the ion path in the body allows reducing the dose to normal tissues during radiotherapy compared to photons. Clinical results of particle therapy support the physical rationale for this treatment, but the method remains controversial. The therapy systems currently installed allow treatment delivery with scanned ion beams with cyclotrons and in some installations synchrotrons as the underlying accelerator. Installations are no longer restricted to huge, multi-room environments but can reach down to single room installations that can physically fit into bunkers originally designed for conventional X-ray therapy. The costs for particle therapy systems, however, are still not yet in the range that allows further spread to smaller clinical centres. The high cost remains the main hindrance to the diffusion of particle therapy.

The vast majority of radiotherapy patients are still treated with X-rays. As of November 2016, 71 particle therapy facilities were in operation and 44 under construction worldwide. In 2015, 16 685 patients were treated with particle therapy, 78% of which were treated with protons and 22% with carbon ions. The number of patients treated per year has doubled in the last decade, an increase that will continue for the foreseeable future.

There are currently five carbon-ion facilities in operation in Japan, two each in China and Germany, and one in Italy and Austria. Several others are under construction or planned, including one in the USA. All of them are synchrotron-based and alternative ions to protons and carbon ions that are currently used in parallel in the European centres are available at the carbon facilities. Investigations on alternative ion species focus on helium and oxygen. Helium has similar biological effectiveness as protons, but reduced lateral scattering, which leads to sharper dose fall-off. Implementation into treatment planning system is ongoing on a research basis but not yet commercially available. Oxygen is interesting for its high biological effectiveness, which could make it a tool for highly radioresistant and hypoxic tumours. The drawback of this ion is its potential toxicity in the normal tissue, which is instead not a major problem for helium.

Boosting of tumour sub-volumes is one type of adaptive treatment schemes. Fundamental necessities of such treatments are adequate imaging capabilities and seamless integration into the workflow. In comparison to photon beam therapy installations particle therapy centres still lack in volumetric imaging capabilities. Some of the recent installations feature in-room CT scanners in diagnostic quality or cone-beam CT systems which are standard for medical electron/photons linacs since several years. Upgrade of existing machines with volumetric imaging or at least installation of such devices in all future particle centres is essential to allow at least patient positioning comparable to photon beam therapy and potentially adaptation of treatment plans on a daily level, to, e.g., allows boosting of changing hypoxic regions or quick adjustment of the treatment plan to shrinking or moving target volumes. In photon beam therapy the currently most advanced system is magnetic resonance (MR)-guided therapy, which is already clinically used in combination with ^{60}Co γ-ray sources. A combination of an electron/photons linac accelerator and magnetic resonance tomography (MRT) is already in clinical use at Utrecht. With the same arguments as above it is thus at least of academic interest to integrate particle therapy and MRT and initial studies in that direction are ongoing.

Another important issue with respect to accelerators and treatment planning is handling of patient changes within a treatment fraction (intra-fractional). Such changes are of main concern if structures moving with respiration are treated with a scanned beam since the resulting interference can result in under-dosage of the clinical target volume. Several beam delivery solutions have been proposed in the last decade. Among them are gating, rescanning, and tracking but also quick treatment delivery options. All techniques should be used in combination with (daily) 4DCT imaging and 4D treatment planning in particular 4D dose calculations to allow a dosimetric estimation of the interplay effect. Facilities with scanned beam delivery need an individual strategy to deal with organ motion and thus the implementation of 4D dose delivery into (commercial) treatment planning systems might be of even higher priority than expansion of accelerator techniques for the mitigation of interplay effects since it can be universally achieved if the delivery parameters (scan time, energy change time, ...) are handled as parameters. Further details are provided in the next subsection Imaging. Individual facilities can then model the interference patterns on a patient specific level and in addition design technical solutions such as fast rescanning, tracking or reduction of scan times towards breath-hold based treatment delivery.

Research in applied nuclear physics, including nuclear interactions, dosimetry, image guidance, range verification, novel accelerators and beam delivery technologies, can significantly improve the clinical outcome in particle therapy. Measurements of nuclear fragmentation cross-sections, including those to produce positron-emitting fragments (used for imaging and range verification), and attenuation curves are needed for tuning Monte Carlo codes, whose use in clinical environments is rapidly increasing thanks to fast calculation methods.

Existing cross sections and codes are indeed not very accurate in the energy and target regions of interest for particle therapy. These measurements are especially urgent for new ions to be used in therapy, especially He and O as noted above. Furthermore, nuclear physics hardware developments are frequently finding applications in ion therapy due to similar requirements concerning sensors and real-time data processing. Parts of the European efforts in the field have been coordinated in the past years by the ENLIGHT platform, based at CERN. Several national efforts are also under way, such as the ARCHADE project in France, which includes the installation of innovative accelerators for therapy in GANIL (Caen), and the FOOT experiment proposed in Italy (INFN) for the measurement of nuclear fragmentation cross-sections. At GSI/FAIR in Darmstadt, the combination of the UNILAC, SIS18 and future SIS100 in conjunction with the supporting infrastructures represents a unique R&D environment for advancements in the field of ion beam therapy.

Imaging

X-ray and nuclear imaging is used in aiding diagnosis and guiding radiation therapies. Anatomical information is acquired from Computed tomography (CT) and Magnetic Resonance Imaging (MRI) whilst functional information can be derived from Single Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET). Developments in detector technologies such as fast scintillators ($LaBr_3$) and solid-state detectors (APDs, MPPCs and SiPMs) have evolved these systems to include Time-of-Flight (TOF)-PET and hybrid PET/MRI, SPECT/MRI capabilities. The improvement of coincidence resolving time (CRT) below 500 ps has significantly reduced the signal-to-noise ratio of TOF-PET images. Further improvement of CRT will provide new opportunities for PET attenuation corrections, whilst 10 ps would provide a new frontier that could lead to reconstructionless PET.

Monte-Carlo simulation is an essential tool for the design and optimization of these new devices and analysis of their data, through informing data correction and image reconstruction processes. GATE, a GEANT4-based package developed by a collaboration of nuclear and particle physicists, is a commonly used platform, with recent upgrades to model light transport in order to support the simulation of optical imaging techniques. Extensive efforts have been made to improve their computational efficiency through the implementation of variance reduction techniques and parallelization on computer clusters or graphics processing units (GPU). In the near future, Monte Carlo will tackle simultaneous imaging and dosimetry issues, and soon case system Monte Carlo simulations may become part of the diagnostic process.

Statistical image reconstruction maximizing the log-likelihood of the measured data using expectation maximisation or a gradient descent optimization has become a clinical realty for about a decade in emission tomography, most often combined with a resampling algorithm of the measured data into sets of 2D sinograms in the case of 3D PET. As an application of the Bayes' theorem, a regularization term can be introduced to limit the expansion of noise through successive iterations. These approaches and list mode reconstruction techniques require an accurate knowledge of the system matrix describing the imaging device, which can be calculated or estimated by Monte Carlo. Predicted physics effects such as scatter and attenuation can be input directly into the reconstruction algorithm. Image reconstruction software packages have arisen for PET and fan-beam or cone-beam CT thanks to dedicated collaborative initiatives, providing access to various implementations of reconstruction algorithms running on different computing architecture, including GPUs. It is recommended that collaborative initiatives are supported with the aim to provide clinically informed, dedicated and maintained image reconstruction and Monte Carlo simulation software packages.

Development of X-ray photon counting cameras based on hybrid pixel detector and ASIC readout arrays provides the opportunity to evolve conventional X-ray CT to spectral CT, including K-edge imaging (see Figure 2). Development of larger CdTe, CZT or GaAs detectors could facilitate translation to clinical practice.

Recent advances in the achievable precision of dose delivery in radiation therapy have promoted the development of instrumentation for in-situ image guidance, from simultaneous stereoscopic radiographic X-ray projections up to integrated volumetric X-ray imaging and, so far limited only to very few installations. This anatomical information of the patient position is used to determine positional corrections to be applied by a robotic positioning system for alignment to the original planning situation prior to irradiation. The new imaging-based representation of the patient can be used to assess anatomical changes, calling for an adaptation of the initial plan to the new situation for ensuring optimal tumour coverage and normal tissue sparing, so called adaptive therapy. Research is ongoing to enable improvements of image quality and computational speed for accurate and fast dosimetric calculations, ideally towards on-the-fly identification of the optimal plan to be delivered to the patient on a daily basis. In addition to anatomical image guidance prior to and, especially for organ motion, during irradiation, more recent developments also aim at devising information on the actual dose delivery. This is particularly important for emerging ion beam therapy techniques, which are extremely sensitive to anatomical variations and other sources of range uncertainties in the fractionated treatment course.

New imaging methods are currently being explored, which either aim at improving the knowledge of tissue stopping properties by using the ion beam itself in transmission imaging, or at indirectly measuring the ion beam range by exploiting secondary prompt or delayed emissions generated by nuclear reactions. Whereas the former approach has not yet reached clinical application and instrumentation development is still ongoing, different techniques and prototypes of nuclear-based in-vivo range verification based on PET and SPECT concepts are being evaluated clinically and will enable soon to draw conclusion on the method of choice, ideally towards real-time control of the dose delivery during therapeutic irradiation. Ongoing advances in imaging will likely impact the therapeutic workflows, substantially contributing to make the most of the high level of precision, which is currently achievable with modern techniques of radiation therapy.

Certain positron emitters emit high energy gamma rays in coincidence with the positron. For example, 99.9% of ^{44}Sc β^+ decays result in the emission of a 1157 keV gamma ray that can be used in conjunction with the detection of the 511 keV annihilation photons. This triggers the development of a novel imaging technique: the so-called 3-photon camera or gamma-PET, which determines the intercept between the line of response defined by the annihilation pair and the trajectory of the third gamma emitted by the radio-isotope. This latter is deduced from a cone of possible incidences given by a Compton camera, for which sophisticated detection techniques such as liquid xenon time projection chambers (TPC) or different combinations of solid-state and/or scintillator-based scatterers and absorbers can be used. Simulations have shown the possibility to achieve good energy and spatial resolutions with this approach and hence reduce drastically the dose injected to the patient.

Last but not least, additional imaging developments are envisaged concomitantly to the use of the bone cancer treatment drug XOFIGO, which is based on the decay chain of ^{223}Ra. In recent years, this radionuclide has been carefully characterized by a number of national measurement institutes

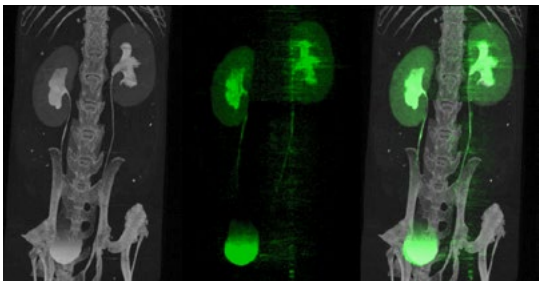


Figure 2: Preclinical K-edge imaging of a mouse injected with iodine, acquired with a photon counting hybrid pixel camera XPAD3. The K edge image (green) was obtained using 3 x 3 composite pixels where energy thresholds were set (from the left) above, under, and at the iodine K

and nuclear data collected during these studies can now be exploited by gamma-ray energy coincidence measurements in order to monitor the dose uptake of this drug.

Radioisotope production

Nuclear medicine describes the use of pharmaceuticals which consist of radioactive materials, either in elemental form or coupled to a molecular vector. This discipline was developed in the 50's with the use of ^{131}I for diagnosis and treatment of endocrine diseases (thyroid). Since then the use of radio-isotopes has been greatly extended to deal with many other pathologies. Over 30 million procedures per year based on radio-isotope compounds are used today in nuclear medicine worldwide. Around 90% of them are dedicated to diagnosis, with ^{99m}Tc representing the most demanded radio-isotope for SPECT. The use of radiopharmaceuticals in diagnosis and therapy is growing rapidly and the radio-isotope market is becoming an important economic driver within the pharmaceutical industry.

Radio-isotopes are used routinely in medicine for both diagnostic (mainly oncology, cardiology and neurology) and treatment (nearly exclusively oncology) purposes. The potential interest of a given radio-isotope in medicine depends on a number of different factors:

- the specific decay properties of the radio-isotope to be used (which dictate its capability for imaging and/or therapy);
- its radiological decay half-life (which must be long enough to reach the target but short enough to avoid unnecessary radiation exposure);
- transport constraints (for example from the production site to the hospital);
- chemical properties (different chemical properties are required for different medical applications);
- the ease of production (quantity, quality, cost effectiveness, availability).

Apart from a few exceptions, the required radio-isotopes should be artificially produced i) in nuclear reactors providing fission products or using neutron capture reactions or ii) in light ion induced reactions at accelerator centres (medical cyclotrons / LINACs).

Most short-lived PET isotopes are produced in a decentralized way at over 700 cyclotrons world-wide. On the other hand the supply of the ^{99}Mo/^{99m}Tc "workhorse" for imaging by gamma cameras and SPECT is presently assured by a limited number of research reactors and processing plants of irradiated ^{235}U targets. To alleviate this potential production and supply shortage, the IAEA has recognized the need to increase worldwide capacity for radio-isotope production and distribution. New facilities can be based on fission reactors, cyclotrons and high-intensity linear accelerators.

Radio-isotopes for therapy

While the use of radionuclides for diagnostic purposes (SPECT and PET) is a mature field in nuclear medicine, the therapeutic use of radionuclides is still less evolved. So-called "targeted therapies" target specifically receptors that are present at the surface of the tumour cells or relevant biomolecules overexpressed in the development of a pathological process. Once in the vicinity of the cancer cells, treatment efficacy resides in the specific radioactive decay properties. Hence, in order to pave the way to a more personalized treatment strategy, radiation types which span different energy deposition ranges within the human body and different associated Linear Energy Transfers (LET) are required. Excellent overall response rates, survival benefit and strongly reduced adverse reactions have been demonstrated compared to standard care, but the clinical use of such targeted therapy has, to date, been limited to niche applications with relatively low incidence, such as thyroid cancer, non-Hodgkin's lymphoma or gastro-entero-pancreatic neuroendocrine tumours.

New applications are currently being developed with new vectors (antibodies, peptides, folates, etc.) targeting more frequent types of cancer such as prostate cancer, lung cancer, melanoma, etc. which kill over 100000 patients in Europe annually. These new developments open the opportunity to combine at an early stage the new vector with a radionuclide of optimized decay properties. For applications where single cells should be targeted, (e.g. non-solid cancers such as leukaemia or lymphoma, micro-metastases of various cancer types), and also for adjuvant treatment of minimal residual disease (i.e. individual cancer cells or cell clusters circulating in the body after surgery or other therapies capable of removing or destroying large, visible metastases) or targeting of chemo- and radiation resistant cancer (e.g. glioblastoma), high-LET particles such as alpha particles or Auger electrons are very promising. Their ranges are comparable to the cancer cell diameter (alpha particles) or to chromosome sizes (Auger electrons) and therefore, a few particles are sufficient to kill even a "radio-resistant" cancer cell.

The challenge for nuclear physics lies in finding ways to provide the most promising radionuclides for such applications since many alpha- or Auger electrons-emitters are indeed "supply-limited".

The theranostic approach

An important challenge of nuclear medicine is to find new techniques able to provide effective cancer diagnostics and treatment at the very early stages of the disease. To achieve this goal, new highly-selective radio-pharmaceuticals are under development, which integrate various diagnostic and therapeutic functionalities:

- selective identification of key precursors of the tumour process;
- early diagnostics of oncologic diseases by using molecular imaging;
- transport and delivery of radio-pharmaceuticals to targeted tumour cells without damaging surrounding healthy tissues;
- real-time monitoring of therapeutic effects during the treatment to redirect/adjust it.

The theranostic approach aims at combining diagnostic and therapy. For nuclear medicine, this translates into combining therapy to efficiently target the cells of interest and highly sensitive and complementary functional imaging techniques.

This new paradigm in nuclear medicine allows in principle to:

- select patients that will respond to a given treatment: optimizing the treatment for each patient;
- assess the staging of the disease;
- perform dosimetry to adjust the therapeutic activity to inject;
- assess the efficiency after treatment.

With such a personalized approach, a better treatment efficacy for the patient and a lower societal economic cost should be achieved.

To this end, specific radio-isotopes need to be developed:

- radionuclides which possess identical ($^{44}Sc/^{47}Sc$, $^{64}Cu/^{67}Cu$, $^{152,155}Tb/^{149,161}Tb$) or similar ($^{99m}Tc/^{188}Re$) chemical properties so that they can be linked to the same molecule
- a single radionuclide for both imaging and therapy (^{117m}Sn; ^{223}Ra);

This is why the whole "nuclear alphabet" involving α, $\beta^{-/+}$, conversion and Auger electrons and α radiations finds useful applications in nuclear medicine, implying the development of numerous radio-isotopes with different decay properties (LET, Q value, $T_{1/2}$) in addition to good chemical properties to ease chemistry with the specific vectors.

Production and mass separation techniques

A necessary condition to promote and develop a personalized strategy is the availability, in a sufficient amount, of high purity and high specific activity of these radio-isotopes.

Production:

These nuclei are produced in nuclear reactors and accelerator centres. Production mechanisms (reaction channels, target / projectile properties, energy) and properties (cross sections, contaminants) should be studied in great detail to assess the interest of potential candidates or vice-versa to enlarge the choice of possible radionuclides.

To be used in nuclear medicine, large radionuclide production is required which implies the use of highly intense particle beams (hundreds to thousands of μA) or secondary neutron sources. Targetry to be used in such conditions (kW of power over few cm^2) are not an easy task requiring dedicated developments. Such R&D activities are ideally suited to be performed in nuclear physics research laboratories. Production capabilities of some specific nuclei using electron and gamma beams should also be investigated.

Purity:

A key characteristic of radionuclides for medicine is "purity". Different types of "purity" have to be considered and first of all the radionuclide purity. The amount of impurities depends primarily on the reaction mechanism itself: reactions induced by low energy projectiles open very few reaction channels, hence tends to result in less impurity, while higher energy projectiles may increase the production yield, though often at the expense of more numerous products. Chemical separation is usually employed to remove unwanted species but it is inefficient for isotopic impurities. Sometimes a suitable combination of irradiation/decay times might lead to a sufficient purity. A second aspect concerns the specific activity. This describes the dilution of the desired radionuclides by stable isotopes of the same element. In particular receptor targeted therapies require high specific activity to avoid saturation of the limited number of receptors per cancer cell by stable atoms. A new approach is the use of physical separation (on- or off-line) using mass separators like at ISOLDE and CERN-MEDICIS. Isobaric separation can provide final products of high specific activity, even in cases where no other way of non-carrier added production exists (production from (n,γ) reaction for example).

Radioprotection

Nuclear physics has largely contributed to radiation protection through the development of detectors and calculation tool. The goals of the radioprotection studies are to evaluate the health risks associated to low-dose radiation exposure and to develop mitigation strategies. In the past few years, radiation protection research has been organized within a European Joint Programme Co-fund Action (EJP). The aim of the EJP is to bring together relevant funding agencies from the EC and the Member States to integrate European research and to administer calls for research proposals in radiation protection on behalf of the EC. This activity will build upon the Strategic Research Agendas (SRAs) from different European radiation protection research platforms and aims to establish interaction and synergies between the different areas of expertise. The radiation protection platforms are: the Multidisciplinary European Low Dose Initiative (MELODI), dedicated to low-dose radiation risk research; European Radioecology Alliance (ALLIANCE) for radioecology and environmental radioactivity research; the European Platform on preparedness for nuclear and radiological emergency response and recovery **(**NERIS), for radiological emergency management; and the European Radiation Dosimetry group (EURADOS), dealing with all Dosimetry issues.

The SRAs define the roadmap and priorities for research to be supported by the EC. The latest MELODI SRA (2015) focuses on three key research questions:

- dose and dose-rate dependence of cancer risk, especially the shape of the dose-response curves at doses below 100 mSv, where epidemiological evidence is scarce;
- non-cancer effects, including cardiovascular and central nervous system late effects;
- individual radiation sensitivity.

The most recent EURADOS SRA covers five topics for future research:

- fundamental dose concepts and quantities;
- radiation risk estimates deduced from epidemiological cohorts;
- dose assessment for radiological emergencies;
- integrated personalized dosimetry in medical applications;
- improved radiation protection of workers and the public.

All these topics require an interdisciplinary effort, including medicine, biology, chemistry, ecology, and of course physics. The EURADOS SRA is particularly addressing the issues of personalized dosimetry, nuclide-specific information in dose rate measurements in the environment, micro- and nano-dosimetry, and accurate dosimetry of neutron fields, where the nuclear physics contribution is essential.

Perspectives and needs

Nuclear Physics has an irreplaceable position in a range of diagnostic and therapeutic practices and in evaluating the radiation healthy risk. To keep and strengthen it:

- Monte-Carlo approaches which combine and validate contemporary imaging, dosimetry and diagnostic processes have to be developed.
- New tools and techniques to improve the quality and computational speeds leading to more accurate and faster dosimetric calculations in real time, thereby optimising patient treatment planning and throughput, should be advanced.
- The development of accelerators and targetry towards intense beams should be promoted
- The study of radionuclide production using suitable and focussed types of nuclear reactions to enlarge the choice of available radionuclides should be encouraged
- Advantage of alternative radionuclide properties to develop new “theranostic” concepts in imaging and therapy should be employed
- The installation of dedicated systems for regular production of radionuclides at existing or projected large-scale facilities should be promoted. Related mass separation techniques to obtain high purity radio-isotopes should be developed.
- Radiobiological studies within interdisciplinary research groups must be supported

ENVIRONMENTAL AND SPACE APPLICATIONS

The interaction of energetic charged particles with atoms can create defects and damages in materials and human bodies. The knowledge of the near-Earth environment in terms of cosmic-radiation is of prime importance for spacecraft operations and astronaut safety. On the other hand, low energetic charged particles are largely used for elemental analysis. Nuclear Physics techniques and knowledge can strongly contribute to get a clear understanding of the Earth and near-Earth environments, which has significant societal and political impacts, and to address the following key questions and related key issues.

Key questions

- What is the part and what is the impact of anthropogenic activities on climate change and modification of our environment?
- What is the radiation content of near-Earth environment and its impact on human activities?

Key issues

- To develop efficient technologies (ion-beam analysis, radiation detection, radiotracers,...) for elemental and radionuclide analysis and to monitor environment changes.
- To reconstruct the past atmospheric concentration of mineral dust to correlate its variations with climatic change.
- To study and identify aerosol sources on a global and local scale and their effects on climate and environment
- Investigate the origin of cosmic radiations and their impact on near-Earth environment

Climate and Earth science

In environmental sciences, Nuclear Physics plays an important role through the measurement of the elemental composition of the aerosol, in particular with Particle Induced X-Ray Emission (PIXE), sometimes complemented by other Ion Beam Analysis techniques (IBA), which is a very sensitive method for detecting trace elements. There is an increasing concern in European citizens about the problems related to the high levels of Particulate Matter (PM) in our cities, which affects human health. Aerosol also affects climate change, directly by scattering and absorption of solar radiation and indirectly by impacting on cloud processes. A large number of abatement measures are beneficial for mitigating both impacts. However there are some measures that may be beneficial for mitigating climate change but increase emissions of the key urban air pollutants, and vice versa.

Regarding atmospheric aerosols, a better knowledge of their composition could help to identify their sources. This would bring valuable information to help epidemiological studies or constraint climate models. PIXE has several prominent features:

- All the elements with Z > 10 are simultaneously detected in very short measuring time (~ 60 sec respect to several minutes or hours typical of other competitive techniques). Therefore, hundreds of samples can be analysed in one day. Depending on the specific problem, any study needs the analysis of a big number of samples to obtain reliable results, of the order of 100-1000. Among the detectable elements, there are also important markers of anthropogenic (e.g., V, Ni, Cu, Zn, Pb) or natural sources (Na, Cl, Al, Si, Ca, Fe, Ti, Sr). Multi-elemental data set as a whole (which comprises data for various tracers) can be used for disentangling the contributions from different source categories by applying multivariate receptor modelling.
- Thanks to the capability of detecting all the crustal elements (which are not detected by Accelerator Mass Spectroscopy (AMS), or with difficulty by ICP-MS), PIXE is unrivalled in the study of mineral dust. Consequently, it is very effective in the study of natural aerosols, like, for example, mineral dust archived in polar ice cores (for environmental and paleo-climatic studies) and Saharan-dust transport.
- It is possible to analyse samples with very low mass: samples collected with high time resolution (e.g. 1 hour instead of 24 hours) to follow the temporal evolution of the aerosol components, as well as size-segregated aerosol samples to assess real human exposure.
- No sample pre-treatment is necessary: this is especially important when samples with very low mass must be analysed and therefore any contamination is dramatic (e.g mineral aerosol in polar ice cores for paleo-climatic studies).
- It is a non-destructive technique; therefore, further analysis by different analytical techniques can be used.

In Europe, several low energy accelerators are operating but only two are particularly devoted to the analysis of aerosol samples, the PIXE Laboratory in Lund and the LABEC Tandem Laboratory in Florence. Other small energy laboratories are partially involved in these studies. In general, their scientific potentiality may cover the largest part of the needs but it is essential to maintain a high level of R&D in these laboratories in order to be able to provide an up-to-date analysis. IAEA, too, is supporting the development of IBA for the study of atmospheric aerosol composition.

Urban pollution

Accelerator based techniques have a role in the study of aerosol composition for the identification of aerosol sources, to give to policymakers the knowledge and the tools for a significant reduction in anthropogenic emissions. The European project

AIRUSE is an example of recent applications. The comparison of data obtained by PIXE and other different techniques (e.g. ion chromatography, those based on atomization by induced coupled plasma and detection by atomic emission spectroscopy (ICP-AES) or mass spectrometry (ICP-MS)) allowed a quality assurance control on the huge quantity of data obtained in the project. PIXE data have been used to reconstruct the average aerosol chemical composition and in multivariate receptor modelling to determine the aerosol sources and their impact on PM smaller than about 10 micrometres (PM 10) and fine PM smaller than about 2,5 micrometres (PM 2.5). In particular the high sensitivity of PIXE for all the crustal elements allowed the direct determination of the Saharan dust contribution. The hourly samples analysed by PIXE helped in disentangling the contributions from different aerosol sources due to the capability of tracking rapid changes as the ones occurring in many particulate emissions as well as in atmospheric transport and dilution processes, thus confirming and reinforcing the identification of the aerosol sources obtained by the daily concentrations.

Natural aerosol

The interest in the study of natural aerosol is justified by the fact that Saharan dust is a major component of PM on a global scale and its atmospheric concentrations have relevant effects on climate and environment; in southern Europe, it gives an important contribution to PM and it can episodically increase significantly the PM 10 and PM 2.5 levels. The EU Air Quality Directives specify that PM 10 limit values have not to be applied to events defined as natural, which include 'long-range transport from arid zones'. Diffusion models and satellite images observation can be very effective in the study of Saharan-dust transport; however, the advection of air masses coming from Sahara does not necessarily imply high PM 10 concentrations at ground level. Therefore, only field campaigns, followed by elemental analysis, can assess the real impact of the Saharan-dust episodes on the air quality, so deserving a key role to the PIXE technique. An estimate of the soil dust component concentration can be calculated considering the crustal elements as oxides. Finally, natural dust contains Fe, an important nutrient in marine ecosystems; the deposition of dust-iron to the ocean affects the carbon cycle and this in turn can affect climate.

Climate

A fine example of the contribution that can be provided by PIXE and complementary IBA techniques is the long-term work that is being done by the Lund PIXE group within CARIBIC project (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container). The CARIBIC is a multidisciplinary project to study gases and aerosols in the mid- and upper troposphere and lower stratosphere by using a civil aircraft on long-distance flights. A Lufthansa Airbus is used since 2004. The Lund group studied the sources of the increase in the lowermost stratospheric sulphurous and carbonaceous aerosol background concentrations, with implication in the areas of nucleation (new particle formation), aerosol optical properties and the role of aerosol particles in cloud formation and properties.

Ocean acidifications

Ocean acidification is a change in pH seawater; CO_2 reacts with water molecules (H_2O) and forms the weak acid H_2CO_3 (carbonic acid). It is estimated that if CO_2 continues to be released at the same rate as today, ocean acidity will increase by 170% compared to preindustrial levels. The changes are happening at least 10 times faster than at any moment in the geological past. Radiotracer applications are essential instruments in evaluating the changes in some key biological processes, e.g. primary production, growth and calcification rates. Programs based on the production and use of radiotracers like ^{45}Ca or ^{14}C are foreseen at radioactive ion beam facilities like SPES and EURISOL-DF. This knowledge is also essential for the risk assessment of coastal ecosystems and the management of the stock of commercial species and to understand the responses of organisms to pH changes. Taking into account the Blue Growth as a key issue for EU, ocean acidification has also the potential to impact the food security and the ecosystem integrity.

Paleoclimatic studies

In order to reconstruct past solar activity, which represents a key variable in paleoclimatic research Accelerator Mass Spectrometry (AMS) provides an excellent tool via measurements of ^{10}Be produced in the atmosphere and extracted from ice cores drilled from stable ice shields, e.g. from Greenland. The reconstructed solar irradiation can then in turn act as a "geological clock" and used to search for its impact on other parameters of relevance for the climate or beyond. As an example, studies of the concentrations of oxygen isotopes could yield information on water temperatures and/or sea level changes.

Insoluble mineral aerosol deflated from continental surfaces is an important player in Earth's climate by its influence on the Earth-Atmosphere radiative budget. To reconstruct the past atmospheric concentration of mineral dust and to correlate its variations with climatic changes, dust stratigraphies have been obtained by the chemical and physical analyses on ice cores drilled in polar areas. For the Southern Hemisphere, ice core drilled in Antarctica can give relevant information on the hydrological cycles of the southern South America (the most relevant dust area for Antarctica during glacial periods) and on the different transport processes of air masses from medium latitude, as a function of the changes in the climatic belts. The isotopic and geochemical composition of Antarctic dust particles both in present-day aerosol and in ice cores is used to infer dust source locations and to study the geochemical evolution, in turn linked to paleo-environmental conditions, of dust at the source. The extremely low elemental concentrations usually present in the insoluble particulate in Antarctic ice cores (pg to µg per kg of ice) make these analyses particularly challenging. In this context, the PIXE technique has proven to be a reliable tool for major and minor elements investigation. Ice-core sections are melted and the liquid is filtered through a narrow-area membrane to concentrate the insoluble dust to obtain detectable concentrations. No other sample pre-treatment is needed, thus minimizing contaminations (compared to ICP-MS).

Perspectives and needs

Recently other competitive techniques, such as ICP-MS/AES have been developed. Furthermore, traditional X-ray fluorescence (XRF) systems have been replaced by more efficient modern devices and synchrotron radiation XRF has started to be used for elemental analysis Therefore, the use of a proper experimental set-up is a prerequisite for a rational application of IBA for aerosol analysis otherwise there is no possibility to compete with the chemistry laboratories. Recently the INFN LABEC laboratory in Florence has developed a dedicated setup which uses an array of new X-Ray detectors which has reduced the measuring time of a factor ten.

It is important to remember that nuclear techniques provide only part of the desired information with regard to the chemical composition (anyway very important). PIXE researchers should not limit themselves to PIXE and IBA analyses, but try to diversify their activities by performing also other chemical and/or physical and optical measurements and to establish collaborations with other groups (chemists, geologists, physicists, ...).

It is important to participate to all the phases of cross-disciplinary projects regarding urban air quality, climate research, ecology, meteorology and epidemiology.

Environmental radioactivity

An understanding of the origin and activity levels of radionuclides present in the wider European environment has significant societal impact, not least in ensuring public confidence in the applications of nuclear science. Accurate measurements of environmental radioactivity levels, traceable to internationally recognized primary standards ensure public confidence in all radionuclide applications. Such applications range from:

- assay and sentencing of medium and long-lived civilian nuclear waste materials including ^{90}Sr, ^{134,135,137}Cs, ^{237}Np and ^{241}Am;
- evaluations of naturally occurring radioactive materials (NORM) concentrations with links to European and world-wide geology, erosion and climate change monitoring such as ^{3}H, ^{7}Be, ^{14}C, ^{208}Tl, ^{210}Po, ^{210}Pb, ^{214}Bi, ^{214}Pb, ^{222}Rn, ^{223}Ra, ^{226}Ra, ^{228}Ac, and ^{234,235,238}U;
- industrially or Technologically Enhanced NORM levels arising from oil scale, produced water and related materials which have potential radiological impact on workers in the oil, gas and wider mineral production industries (e.g. ^{40}K, ^{219,220,222}Rn, ^{223,234,236,238}Ra, etc.);
- the production, handling and disposal of important radiopharmaceutical isotopes such as ^{82}Rb/^{82}Sr, ^{89}Zr, ^{99m}Tc, ^{131}I, ^{211}At, ^{223}Ra and ^{227}Th.

Gamma-ray spectrometric measurements of environmental samples allows a careful evaluation of NORM levels across a range of naturally occurring radioisotopes and can also be used to determine uranium isotopic ratios which are signatures of uranium depletion or enrichment. There are also a number of cases where gamma-ray spectrometry is not suitable for such activity determinations and other techniques such as alpha-particle spectrometry are required including the direct decay of ^{238}U and ^{232}Th and/or liquid scintillation counting for ^{3}H and ^{14}C measurements.

This public confidence in such pursuits stems from the parallel strands of accurate, traceable measurement underpinned by careful management and evaluation of nuclear decay data (see Figure 3). Indeed, nuclear data are essential for many applications related to measurements of environmental radioactivity, including decay products

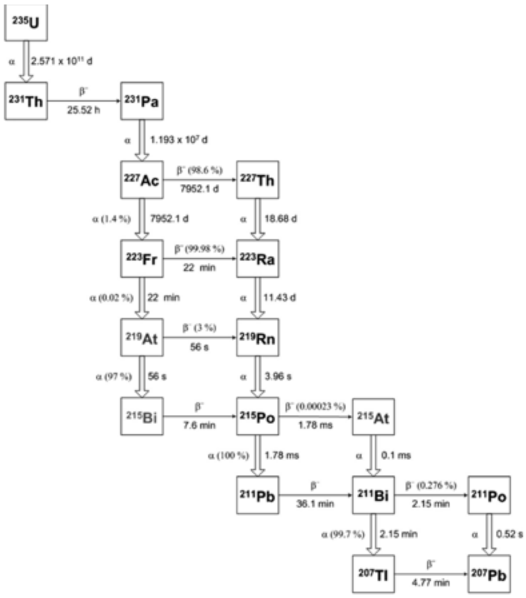


Figure 3: Evaluated decay data for the natural decay chain of ^{235}U.

from nuclear power production and verification of International Comprehensive Treaty Ban Organisation commitments through atmospheric measurements of signature fission and activation products such as ^{111}Ag, $^{125}Sb/^{125}Sn$, ^{131}I, $^{140}La/^{140}Ba$. The availability of reliable, up-to-date and well-structured data libraries, with user-friendly visualization and retrieval tools, are indispensable in this regard. Credible and reliable nuclear data libraries have a profound societal impact by connecting science and technology with society through dissemination of the results of basic nuclear physics research.

Perspectives and needs

The European nuclear physics community must upgrade its expertise in the measurement and characterisation of radioactive sources across the wider environment to ensure public confidence in applications of nuclear science. This includes needs for up to date measurements on key nuclear decay data such as half-lives and gamma-ray emission probabilities values for a the most important environmental radioactive sources.

Reliable, recommended nuclear data libraries are required in a wide range of applications that possess strong, direct societal impact. Strong support for nuclear data evaluation activities within the various topical fields included in the Long Range Plan is needed.

Space radiations

Space radiation characterization and dosimetry

Understanding the near Earth and radiation belt environment composition and variability has important practical applications in the areas of spacecraft operations, spacecraft system design, mission planning and astronaut safety. The composition and origin of space radiation in the near-Earth environment are of different types, exhibiting high variability in intensity and energy spectrum. The main components are (i) galactic cosmic rays which originate outside the solar system, (ii) energetic and transient solar particle events which are emitted by the Sun, and (iii) the trapped radiation in the Earth radiation belts. Further contributions to the radiation field result from secondary particle in the spacecraft itself and from the interaction of energetic cosmic rays with the Earth's atmosphere including albedo neutron production. On Mars, secondary radiation is produced by the thin atmosphere and by the scattering on the planet's surface. On the Moon the nearly entire absence of an atmosphere results in a greater contribution of secondary production from cosmic ray interactions in the lunar soils and regolith. The resulting composition, intensity and energy spectra of the radiation field are very broad, exhibiting large gradients with altitude, which also show large temporal variations.

The resulting absorbed dose rates reflect a corresponding broad spread (over many orders of magnitude for a Moon- or Mars-bound flight across the Earth's radiation belts) and time variability (also over many orders of magnitude for strong solar particle events). The recent measurements of the Radiation Assessment Detector (RAD) on the Curiosity rover (Mars Science Laboratory) (Figure 4) demonstrated that the total dose in a mission to Mars is close to 1 Sv, making radiation the major health risk for human exploration. In addition to passive solid-state instrumentation there is active in-situ dosimetry on board the International Space Station. Advanced instrumentation is also being deployed providing high-resolution radiation monitoring (examples include energetic particle telescopes (e.g. EPT) and integrated particle spectrometers, e.g. MagEIS and the Relativistic Proton Spectrometer both on board the Van-Allen radiation belt probes).

Figure 4: The NASA Mars Science Laboratory (MSL) spacecraft had onboard the Curiosity and a radiation detector (RAD), which has been used to measure the dose in deep space during the transfer to Mars (November 2011-August 2012) and on the planet's surface (photo courtesy of NASA)

Ground-based research

Accelerator-based simulations are very important to perform space radiation protection experiments. Radiobiology studies in cells, tissues, and animals, can be performed at accelerators to predict health risk in long-term manned space missions. NASA sponsors a large program in the field at the Brookhaven National Laboratory in Upton, NY, and ESA has sponsored similar European activities called Investigation on Biological Effects of Radiation (IBER), based at the SIS18 synchrotron at GSI. Many experiments have been performed using ^{56}Fe at 1 GeV/n, being iron the most abundant very heavy ion on the galactic cosmic ray spectrum, and considering that these ions at this velocity have an LET around the peak of effectiveness for biological damage.

In the future, the FAIR accelerator will be an ideal site for this research, given the higher energies of heavy ions that will be possible to reach there. FAIR will be indeed the only accelerator able to produce all beams at virtually all energies of interest for applications in space radiation research and medicine. High-energy proton and heavy ion accelerators can also be used for testing shielding materials. Attenuation of high-energy and high-Z beams gives indications on the quality of the shielding material. Light, hydrogen-rich materials, give stronger dose attenuation than high-Z shields at the same mass thickness (in g/cm^2). High-energy proton beams directed on thick shields simulate the production of secondary radiation, especially neutrons, in spacecraft and planetary bases. These data are also important to benchmark transport codes, especially Monte Carlo, used for space radiation. Low-energy accelerators have been used to test damage to microelectronics in space, and their role remains essential to measure single event upsets, latchout, burnout, etc. Recently high-energy particle tests for radiation hardness have also been performed. With high-energy beams entire, unopened devices can be tested, and range effects can be assessed before spaceflight.

In complement, ELI-NP is a unique facility that can generate as secondary radiation intense multi-component, multi-energetic, space-like radiation in ground-based laboratory conditions, by the interaction of two pulsed laser beams (1 PW, 25 fs) with solid or gaseous targets, in a large interaction chamber. The method of irradiating biological samples with intense radiation that has a wide spectrum is a closer model when compared to typical radiation sources used in today's space radiation testing facilities, cyclotrons and electron linacs which can generate only highly mono-energetic radiation. In a deep space mission a spacecraft with human crew will mostly encounter multiple, different kinds of space radiation. Studies on the interaction of biological systems with intense ionizing radiation mimicking space radiation will foster advances in knowledge and technology that will help to develop effective countermeasures for health effects related to chronic radiation exposures. Also, it will provide an improved, evidence-based radioprotection system for deep space missions with human crew and for the establishment of permanent human habitats on Mars.

Cosmic ray physics

Current space radiation research includes dedicated studies of high-resolution characterization of the galactic cosmic rays. Experiments are motivated by astrophysics studies such as the origin of energetic cosmic-rays and particle propagation/transport in the solar system and at the galactic scale. The space-borne particle-physics experiment AMS-02, in Low Earth Orbit (LEO) since 2011 on board the ISS, performs high-resolution measurements of cosmic ray composition and spectra including measurements of the anisotropies of the positron and anti-proton distributions. Results include fundamental physics studies such as investigations of dark matter. The PAMELA cosmic ray space observatory, deployed since 2006, measures the composition and spectra of cosmic rays and trapped radiation in LEO orbit. A fully European project, PAMELA is the first satellite-based experiment dedicated to the detection of cosmic rays, with a particular focus on their antimatter component, in the form of positrons and antiprotons. Other objectives include long-term monitoring of the solar modulation of cosmic rays, measurements of energetic particles from the Sun, high-energy particles in Earth's magnetosphere and Jovian electrons.

Space weather, Earth magnetosphere

Related research includes space weather and the physics of Earth's geomagnetic field and the interplay with solar wind and energetic solar radiation. Earth bound solar particle events and coronal mass ejections can strongly affect the magnetosphere and distort the distribution, composition and dynamics of Earth's radiation belts resulting in the energetic and highly variable phenomena of geomagnetic storms, which can potentially disrupt spacecraft systems and satellite navigation. The geomagnetic field serves primarily as shielding against energetic cosmic rays while it also accumulates charged particles, forming the radiation belts. Current research includes novel phenomena/processes of acceleration, depletion of the trapped radiation, creation of energetic charged particles in the Earth's belts. For this purpose dedicated space missions are being deployed in orbit such as the Radiation Belt Storm Probes (RBSP - also called Van Allen probes). Launched in 2012, the RBSP consist of twin spacecraft sampling the Earth belts along highly eccentric orbits reaching high altitudes enabling systematic and correlated measurements.

SOCIETAL APPLICATIONS

Nuclear techniques are high-precision non-destructive methods used to characterize samples at the elemental level bringing new insight compare to other methods. That is the reason why these methods are more and more used in the interpretation and the preservation of cultural heritage and for the control of radioactive materials.

Key questions

- Which technical developments strengthen the position of nuclear techniques compared to other methods?

Key issues

- Safe boundaries of nuclear techniques to minimise the side-effects of the applied radiation
- Development and use of instrumentations with more modalities
- Access to analytical facilities and communication with end-users

Heritage science

Heritage science is a multi-disciplinary domain dealing with the various aspects of cultural and natural heritage conservation, interpretation and management. It operates across the boundaries of arts and humanities, as well as science and technology. Nuclear physics contributes to the field with a wide range of analytical methods to determine the composition, or the age of tangible heritage. It also has a role in the preservation of art and archaeological objects.

Ion beam analytical techniques

IBA techniques have been used for decades to analyse archaeological and art objects. Their main strength is their analytical performance which reaches the trace elemental level, without sampling. The possibility to obtain the distribution of elements through mapping, depth information, and the capability to measure light elements are of great importance to preserve the position of these techniques in the plethora of analytical methods.

Although IBA techniques are considered non-destructive, since no sampling is needed, the irradiation may cause visible or non-visible, reversible or irreversible changes depending on the material and the experimental parameters. (This is also true for photon irradiation.) Therefore establishing the safe boundaries are of outmost importance. The IBA and the photon irradiation communities have launched an initiative to be more open about this issue, with the help of IAEA, and also as part of an IPERION CH (*Integrated Platform for the European Research Infrastructure ON Cultural Heritage)* research programme. More systematic investigations as well as specific guidelines are expected. One of the obvious mitigation strategies is to decrease the beam current and the time of acquisition. To do that, efficient detector systems are required. The AGLAE Laboratory, for example, has managed to gain a factor of ten for trace elements analysis with their new detector configuration (see Figure 5).

The competition of synchrotrons and bench or even portable techniques has been increasingly stronger. However, the high quality of IBA results with their fully quantitative nature, and the adaptability of the experimental settings are still very attractive. Besides the most prevailing PIXE/PIGE/RBS methods, we can expect the increase

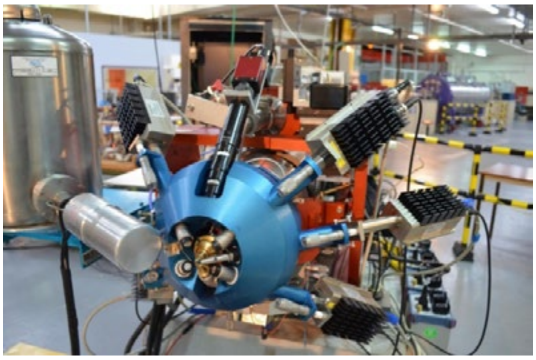


Figure 5: The multi-detector system on the AGLAE external beam (NIMB 318 (2014) 27)

of the applications of other modalities such as ionoluminescence, or X-radiography induced by PIXE. Although most investigations in the field are performed with external beams, measurements in vacuum have also their use, especially when high spatial resolution, light element PIXE (down to carbon) or hydrogen detection are the goal (e.g. archaeogeology, research on consolidation materials, etc.)

Neutron techniques

The strength of neutron techniques is in providing information about the inner structure and composition of objects in a non-destructive way. The methods cover elemental (or even isotopic) analysis, diffraction and imaging which are valuable tools to determine the characteristics of art and archaeological objects. Neutrons penetrate through the outer, often corroded or otherwise altered layer and travels through the selected volume. The different available methods can be combined such as in the radiography/tomography-driven Prompt Gamma-ray Activation Imaging facility, constructed in 2012, in the Budapest Neutron Centre. Neutron imaging is complementary to X-ray imaging as the transmittance differ for the elements; it is useful to also have an X-ray system in neutron facilities. Phase contrast imaging and energy selective imaging are among the new trends. The ability of the neutron techniques to look below the surface is highly thought-after but the accessibility of research reactors and spallation neutron sources is a limitation.

Carbon dating and preservation of cultural and natural heritage

Besides the composition and structure of tangible heritage, the two most important issues related to nuclear physics are dating and preservation. The number of AMS facilities is increasing in Europe and more compact facilities are also available. For heritage science applications the sample preparation is at least as important as the measuring part, special efforts (graphitization units, carbonate sampling systems, etc.) are required to ensure high quality. For bone samples, stable isotope measurements are also needed for a precise dating.

Preservation requires high intensity gamma-rays to kill bioactivity (disinfection) or for consolidation by radio-polymerisation. The number of dedicated facilities is small and side effects must be considered. But as irradiation acts on all biological aggressors and large amount of objects can be treated simultaneously, and the modification can be kept at an acceptable level with proper expertise, this is a valuable tool for conservators.

Complementary gamma-ray techniques

High-energy, monochromatic gamma-rays are the ideal probe for non-destructive investigations of large and complex archaeological artefacts and works of art. Nuclear resonance fluorescence (NRF) based methods and gamma-ray beam radiography and tomography using very intense gamma-ray beams of small bandwidth and high energy will allow high-resolution 2D/3D imaging and in-depth elemental analyses of large objects of various nature and composition. In practice, the gamma-ray beam is tuned to the energy of a specific state of a nucleus of interest and the resonant absorption of gamma-ray is monitored. The availability of a high efficiency gamma-ray detection system will allow for high sensitivity NRF measurements, which coupled to radiography and tomography analysis can produce isotope-specific trace element distributions in bulk materials. Nuclear resonance fluorescence provides selectivity for all elements without noticeably affecting the investigated objects. This is a key aspect for applications such as trace element analysis of Cultural Heritage objects. The development of this field depends greatly on NRF data availability, high efficiency detection system and on interdisciplinary collaborations.

Access to analytical facilities

In the field of heritage science, the access to nuclear physics techniques is not always straightforward. After the successful EU CHARISMA project, currently the IPERION CH provides access to large scale facilities in France (AGLAE, SOLEIL) and Hungary (BNC, MTA Atomki) for users in the field. The CERIC consortium also accepts proposals from heritage science. Many laboratories have good personal contacts with museums and have recurrent users. Nevertheless, these techniques are still not as well-known as they should be. Many publications appear in technical journals which are beyond the usual pool of journals read by archaeologists, conservators and curators and these experts often do not feel encouraged enough to apply for these techniques. The EPS Nuclear Physics Cultural Heritage Topical Paper (2016) can be one possibility to reach out to stakeholders. A unique opportunity emerges with the acceptance of the European Research Infrastructure for Heritage Science (E-RIHS) initiative for the ESFRI Roadmap. E-RIHS will provide state-of-the art tools and services to the multidisciplinary communities of researchers working to advance knowledge about heritage and strategies for preservations. Techniques based on the principles of nuclear physics are embraced within E-RIHS as tools which can provide valuable insights into historical technologies, materials, chronologies, and degradation phenomena.

Perspectives and needs

Nuclear Physics continues in providing essential tools and methods for a multi-disciplinary domain of heritage science. To take full advantage of this position:

- Use of the maximum number of simultaneous modalities to gain the maximum information during the irradiation is needed
- Detection systems for higher efficiency and safer irradiations must be upgraded
- More synergy with other physical and chemical techniques should be promoted
- Better communication with stakeholders have to be set
- Participation in and support of E-RIHS is a crucial element

Nuclear security and counter terrorism

The European Internal Security Strategy draws attention to the need to enhance capabilities against CBRNE (chemical, biological, radiological, nuclear, explosives) threats, including developing minimum detection and sampling standards.

The action plan focuses on three main strands:

- Prevention: ensuring that unauthorised access to CBRNE materials of concern is as difficult as possible.
- Detection: having the capacity to detect CBRNE materials to prevent or respond to CBRNE incidents.
- Preparedness and response: being able to efficiently respond to incidents involving CBRNE materials and to recover from them as quickly as possible.

The action plan includes both legal and technical measures to mitigate the threats related to malevolent use of nuclear technologies and terrorist attacks involving radioactive materials and to have an efficient control at border posts to trace any transport of radioactive material. Issues not currently being adequately addressed at European level include certification of radiation detectors, standardization of deployment protocols, response procedures and communication to the public. Existing techniques could be enhanced by reference to standards that would better support field teams when detecting and analysing radiological contamination. The idea would be to provide a framework within which experimental facilities and laboratories will share knowledge and expertise in order to harmonize test protocols throughout Europe, leading to better protection of critical infrastructures against all types of threats and hazards. The mission is to foster the emergence of innovative, qualified, efficient and competitive security solutions, through the networking of European experimental capabilities.

Future data acquisition systems shall enable the movement of detection data from first responders electronically to analysis centres rather than the costly and time consuming process of moving experts and/or samples. This new technology is especially useful in crisis events, when time and resources are sparse and increased analysis capacity is required. In order to utilise the opportunities opened by these new technologies, the systems have to be interoperable, so that the data from each type of detector can easily be analysed by different analysis centres. Successful interoperability of the systems requires that European and/or international standards are devised for the digitised data format. The basis of such a format is a list of registered events detailing an estimate of the energy of the detected radiation, along with an accurate time-stamp for recorded events (and optionally other parameters describing each event).

Improved radiation detection systems

In nuclear security, the detection of illicit trafficking of nuclear material (particularly plutonium) is at present based on the use of ^{3}He detectors for the detection of the characteristic neutron emanations in radiation portal monitoring systems. The recent significant increase in the demand for instrumentation related to nuclear security, coupled to the reduced production of nuclear weapons, has created an issue with ^3He detector supply from manufacturers, leading to an associated exponential price increase.

Recent research into alternative detection systems has given preliminary indications that some novel and promising alternatives may be employed. In the last 10 years a large number of new high light-yield scintillator materials have been discovered. The first and the most famous among them, the Lanthanum Halides, were already the target of an intense R&D, which provided the starting point for the design and development of several new high performance $LaBr_3$:Ce, $LaCl_3$:Ce based detector arrays. A suite of "new" detector technologies and systems are currently emerging as $CeBr_3$, SrI_2 but others as CLLB (Cs2LiLaBr6:Ce), CLYC (Cs2LiYCl6:Ce) or CYGAG:Ce (a transparent ceramic material exhibiting promising scintillation properties and offering the advantages of a ceramic in terms of robustness and chemical stability) require intense R&D activities in order to fully characterise their properties.

Combining two or more scintillator materials in a single compact detector can be a cost effective way of detecting gamma-rays, charge-particles and neutron radiations with the same detector. Adding a segmentation of the crystals could give also new imaging features that can help in detecting the angle of impact and thus the direction of the source relative to the detector.

List-mode data acquisition based on digital electronics

Time-stamped list-mode data format produces significant added value compared to more conventional spectrum format. It improves source localization, allows signal-to-noise optimization and noise filtering. List-mode approach also allows precise time synchronisation of multiple detectors enabling, for example, measurement of single gamma-rays in one detector and UV-gated gamma spectrometry in other ones. List-mode data is commonly used within the nuclear physic community but has up to now not been used in the area of nuclear security.

The development of Time- and Geo-stamped correlation is important to be able to scan big objects from a car or an aeroplane or large areas. Such technology is also needed to follow the movement of malicious activities over long time scale.

Remote-controlled radiation measurements

There is significant potential for the use of unmanned remote controlled systems in sampling and measuring radiological events. The main advantage is the protection of the involved human personnel. Depending on the size and the loading capacity of the unmanned system, appropriate sensors are necessary. The main envisaged applications are:

- repetitive/routine measurements;
- measurements in areas of high radiation;
- search, localisation and identification of possible radiation sources;
- gamma-ray mapping: dose rate, surface activities, point activities (including blank of critical infrastructures and sites);
- operation in dangerous and uncooperative environments (CBRNE scenarios, dirty bombs, inaccessible areas, etc.);
- collection of samples;
- decontamination and containment actions;
- forensic medical applications as in case of *radiological-dirty* crime.

Reachback and expert support

Most countries have emergency-plans to deal with accidents of different kind and scale. However, only major powers have the capability to keep continuous track and history over the RN measures within their borders and thus be able to search and prepare for criminal activity. For an efficient Reachback system which covers all the territories there is a need for standardizing data taking, storing, and the final distribution of the analysed data. A European centralized database where all information are stored and can be analysed from different laboratories should be created to have 24h 7/7 days control all over Europe.

Nuclear Forensics

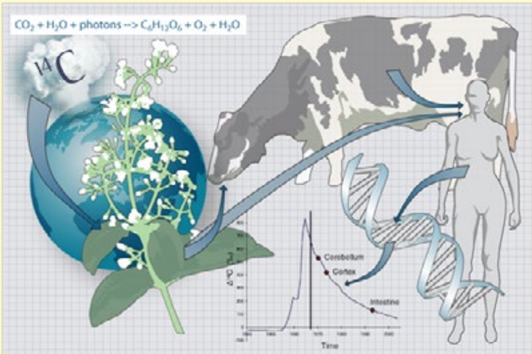
Non-destructive investigations based on brilliant gamma-rays can be successfully applied to nuclear security and counter terrorism. Active interrogations based on nuclear resonance fluorescence (NRF) have the potential to determine the isotopic composition of a sample or the fractional abundances of a specific isotope, which are of great interest in the spent fuel composition analysis, uranium enrichments and waste management. The two detection methods used for NRF based active interrogations are the scattering and self-absorption (or transmission) methods. In both cases the gamma-ray beam

Box 2: Nuclear Analysis Methods and the Biomedical Bomb-Peak Dating

Nuclear methods and methods based on nuclear techniques are extremely efficient and, in many cases, unique tools for investigating the structure of materials and to characterize samples at the elemental level. This method benefits from progresses in accelerator technology and instrumentation to increase their sensitivities.

Among them, Accelerator Mass Spectrometry (AMS) analysis is a powerful technique to measure the isotopic ratio of elements in materials. Coupled to the conventional Carbon-14 dating method, it offers new opportunities. Carbon-14 dating method is a robust and well established tool in the archeological sciences, facilitating dating artefacts from tens of thousands of years ago to the middle of last century with an accuracy of few tenths of years. The so-called "bomb-peak dating" addresses the interesting period of the last sixty years with an accuracy of about two years. Detonation of the atmospheric nuclear bombs during the Cold War years, prior to the Test Ban Treaty in 1963, increased the amount of radio-carbon in the atmosphere significantly, providing a time marker.

By improving the sensitivity of AMS analysis from requiring milli-grams amounts of asample material to micro-grams, it has been able to address a number of hitherto uncharted scientific questions such as: "How old are the various cells in our body?" As an example, using purified DNA, the regeneration rates of neurons in hippocampus and striatum in the human brain have been measured showing high levels of renewal. Other highly controversial questions regarding the human cardiomyocytes (heart muscle cells), the adipocytes (fat cells), oligodendrocytes (brain support cells) have now been resolved using this technique. In this domain, the objective is to have a complete regeneration map of the human cells in health and in disease.



Other applications can be found to provide court-of-law evidence for a number of actual forensic cases. For instance, human teeth have been dated to confirm the date-of-birth of the victims. An extreme sensitivity of AMS for ^{14}C labelled pharmaceutical substances in human blood in the zepto-mol range (10^{-21} mol) has also been demonstrated. This is of pronounced interest in the pharmaceutical industry. Minute amounts of candidate drugs are administered directly to humans, yielding pharmacokinetic data which are critical in early drug development – the so-called Microdosing method.

is used to resonantly excite nuclei while the de-excitation photons are detected in different geometries. The performance of these methods is greatly improved by the recent development of very intense, mono-energetic gamma-ray sources of MeV energies. Consequently, a tuneable energy gamma-ray beam of high spectral density coupled with a high efficiency gamma-ray detector satisfy the criteria for high sensitivity NRF measurements enabling mapping of specific isotopic/elemental distributions in objects with single resonance resolution. While the application of the NRF method shows great promise there are still technical issues that needs to be overcome. For instance the lack of available data about the NRF resonances of many nuclides is a hindrance to the development of this field, which needs to be addressed and an extensive database needs to be developed.

Perspectives and needs

Efficient security and antiterrorism activities in nuclear domain require implementation of both, legal and technical actions. Legal activities to the large extent overlap with intellectual and commercial property protection as well as with the export control measures. It is thus possible to implement a common procedure allowing for rapid classification whether a given activity (e.g. sample transfer or data publication) may be freely conducted or may require additional verification.

For that, from the nuclear physics perspective:

- Development of detectors with directional detection and with simultaneous gamma-ray and particle identification is needed.
- High priority should be given to the standardisation of list-mode data with Time and Geo-localisation.
- Lightweight detectors and manipulators should be developed for remote-controlled

radiation measurements.

- The emergence of innovative, qualified, efficient and competitive security solutions, through the networking of European experimental capabilities should be promoted.
- An extensive database of resonances of stable and long-lived nuclei of interest is needed

CROSS-DISCIPLINARY IMPACT

Nuclei interact with matter mainly by electromagnetic interaction. The use of ion beams is then well suited to study the structure of materials and atomic matter even in extreme conditions as in plasma.

Key Questions

- What are the local and long-range chemical and magnetic structures of materials?
- What are the dynamical properties of materials and how do ultrafast processes take place in materials?
- How do atoms and materials behave under extreme conditions?
- How can materials be modified by nuclear tools?

Key Issues

- Increasing sensitivity, increasing depth and lateral resolution of analytical techniques
- Extending the temperature, pressure and magnetic field range accessible for nuclear methods
- Controlled modification and nanostructuring of materials

Materials sciences

Nuclear physics has provided a number of valuable tools for materials science, the vast majority of which features the possibility for non-destructive analysis. An additional benefit is the fact that many of the methods yield quantitative results without the requirement of reference samples. Most commonly, keV and MeV ion beams provided by accelerators are employed for materials characterization or modification. In the field of ion-beam analysis (IBA) continuous development of the established methods is performed towards more sensitive systems with enhanced depth resolution to meet the ongoing trend of miniaturization in thin-film technology as well as to be able to employ the methods e.g. for soft-matter systems. Methods like medium-energy ion scattering (MEIS) or MeV-secondary-ion mass spectrometry (MeV SIMS) with micro-beams or for ambient conditions are examples of ongoing developments. A larger penetration of ion-beam based analytical tools into e.g. organic thin film chemistry can be expected, but requires active communication of the potential of the methodology beyond the established target communities.

Radioactive ion beams (RIB) have been extensively used in materials sciences and related multidisciplinary research (e.g. in the form of hyperfine interactions and channelling techniques), with Europe playing a particularly dominant role. ISOLDE at CERN is at the forefront of such applications, providing the largest diversity of radioisotopes from elements which are relevant in a wide range of research domains (fundamental and applied). While the continuous development of RIB facilities has greatly increased the number of isotopes that can be used, their applicability remains relatively limited since the radioisotopes are typically delivered within a small energy window (tens of keV). Crucial developments towards the generalized use of these new capabilities involve delivering radioactive ions under conditions that are suitable for a wider range of users and research domains, through the development of, for example, controlled beam deceleration for applications in material sciences (e.g. thin-films and surfaces), or implantation into liquid media for applications in chemistry, biology and medicine. European RIB facilities are already pioneering such developments (e.g. the VITO project at ISOLDE) and further initiatives and support will be required to maintain Europe's leading position.

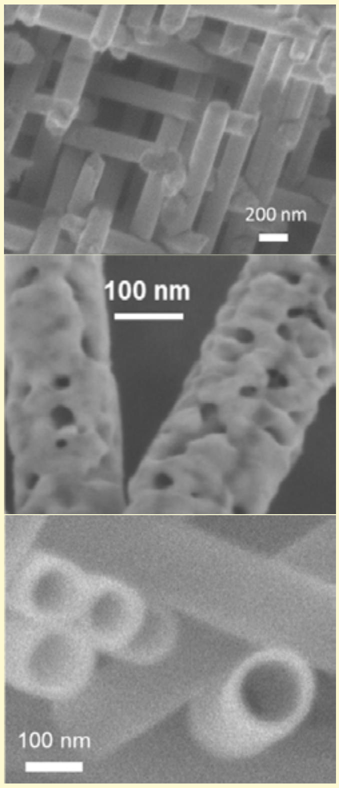
There are also numerous non-ion-beam-based techniques which originated from nuclear physics and have great potential for materials characterization and for studying physical and chemical phenomena in materials.

Neutrons have been widely used as analytical tools in activation analysis and radiography of bulk materials. The main strength of thermal neutrons is their applicability in scattering experiments: diffraction methods being sensitive to long-range chemical and magnetic structure while small-angle scattering and reflectometry give insight to short-range properties of nanostructured materials. With the advent of ESS, Europe will further secure its leading role in neutron scattering in a period when, by decommissioning many nuclear reactors worldwide, we shall be faced with a dramatic shortfall of research neutrons.

Mössbauer spectroscopy (including nuclear resonant scattering of synchrotron radiation)

Box 3: Materials Science and Nanotechnology with swift heavy Ions

Existing high-energy ion accelerators (such as GSI, GANIL, Lanzhou) and the future facility FAIR provide unique opportunities for materials research with ions of several hundred MeV energy (and above) in many different disciplines including nanotechnology, solid state and surface physics, crystallography, mineralogy, geosciences and biology. Swift heavy ions deposit enormous energy densities into the solid, driving the local atomic structure far from equilibrium and resulting in rapid phase transitions and complex structural modifications along the ion trajectory. These long cylindrical trails of severe damage enable swift heavy ion beams to be used as tool for producing nanostructures of high aspect ratio. By combining track etching, electrochemical deposition and surface modification techniques such as atomic layer deposition, nanostructures with designed diameter, length, shape and composition are synthesized (examples shown in figure). This enormous flexibility allows e.g. exploring size-dependent thermal, electrical, plasmonic and chemical properties of nanowires and is promising for applications of nanowires, -tubes and -channels as nanosensors, nanoelectrodes or nanofluidic devices.



Novel ion-track technology based nanostructures such as nanowire networks (top), porous wires (center) and nanotubes (bottom) with tailored diameter, length and surface.

In addition, irradiation of materials with swift heavy ions results in effects such as, local melting, shock waves, permanent changes of materials properties and the emission of secondary particles. Injecting for instance relativistic ions through a mm-thick diamond anvil cell into a target under high-pressure, drives the local atomic structure far from equilibrium. Such conditions provide unique pathways in the phase diagram that simulate conditions existing in the Earth mantle, and which result in the stabilization of new material phases at ambient conditions, which are otherwise not accessible. Furthermore, testing materials behavior in extreme radiation, pressure, and temperature environments will also have a direct application to the understanding of degradation processes of functional materials in next generation high-power accelerator components, fusion and fission reactors. Of great importance is the development of new material solutions for extreme cases and shielding of equipment in deep space missions.

and perturbed γ-γ angular correlation (PAC) are methods mainly based on hyperfine interactions. Especially Mössbauer spectroscopy has a wide range of applications including metallurgy, solid-state physics, magnetism, structural chemistry, nanosciences, life sciences, archaeology, etc. Besides, nuclear resonant scattering of synchrotron radiation comprising resonant forward scattering (both in time and energy domain), nuclear inelastic scattering and synchrotron radiation perturbed angular correlation has been recently extensively used for studying vibrational properties of materials, particularly at extreme conditions with an important impact to earth sciences. Mössbauer spectroscopy has traditionally been worldwide the strongest in Europe. Nuclear resonant scattering beamlines in Europe are available at ESRF and PETRA III. With the envisaged upgrade of the ESRF beamline ID18 a beam size at the sample position of 150 nm × 50 nm and an energy resolution of 10 μeV can be reached, an unprecedented tool for studying nanosystems.

Muon-spin rotation (μSR) and positron annihilation spectroscopy are nuclear methods in a more general sense. μSR has a significant impact to diffusion and magnetic structure studies. The main strength of positron annihilation is its extreme sensitivity to defects in materials such as vacancies and dislocations. With the advent of slow-positron sources (both those based on radioactive sources as well as those based on LINACs or nuclear reactors), the method became surface-sensitive; an important aspect in nanoscience applications

The field of materials modification by nuclear physics methods is dominated by ion irradiation, most commonly with several ten to hundreds of keV, with large volume applications such as semiconductor doping or material amorphization.

Research is expected to focus in two directions: first, materials modifications in rather extreme environments, i.e. under extreme doses or other complex environmental conditions is of relevance for research in fusion as well as next generation fission reactors and has applications in earth and planetary sciences. Second, shallow implantation of low doses with high lateral selectivity, in the best case controlled single ion implantation is of relevance for the growing research fields of spintronics and qubits in quantum computing.

With the availability of high-intensity laser beams as at the ELI-NP new facility, it will be possible to develop innovative research in the fields of materials behaviour in extreme environments. The proposed studies will take advantage of the specific properties of the laser-driven radiation production, such as ultra-short time scale when the radiation is generated, and the relatively broadband spectrum of radiation, complementary to that generated in traditional nuclear physics laboratories. Additional specificity of the proposed experimental environment for tests at ELI-NP is that it could provide simultaneously several types of radiation on the same target. The expected radiation beams to be achieved at the ELI-NP in the initial phase are as follows: laser accelerated electron beams (maximum energy 2 GeV and maximum intensity 10^8 e/pulse), laser- accelerated proton beams (maximum energy 60 MeV and maximum intensity 10^{12} p/pulse) and laser-driven neutrons (maximum energy 60 MeV and maximum intensity 10^7 n/pulse). The unique feature of the ELI-NP facility is the availability of two high-intensity short-pulse lasers that would enable pump-probe experiments using laser based diagnostic allowing for structural degradation studies during irradiation on a much finer time scale.

Nuclear physics in general and the advanced large nuclear physics facilities in particular provide unique opportunities for materials research. To fully explore such an innovative potential, schemes that link operators of applied nuclear facilities to potential user groups in materials sciences and related areas must be extended and cultivated

Atomic and Plasma physics

Upcoming large scale particle accelerator facilities such as FAIR, ISOLDE and SPIRAL2, provide outstanding and worldwide unique experimental conditions for extreme matter research in atomic and plasma physics. The associated research programs comprise interaction of matter with the highest transient electromagnetic fields and properties of plasmas and of solid matter under extreme pressure, density, and temperature conditions.

A broad variety of dedicated experimental facilities, including experimental stations, storage rings, and traps, equipped with most sophisticated instrumentation will allow the atomic and plasma physics communities to efficiently exploit the unique research opportunities and to tackle the associated new challenges.

Atomic physics research will focus on the study of atomic matter – ions, atoms and molecules - subject to extreme electromagnetic fields as well as atomic processes mediated by ultrafast electromagnetic interactions (see Figure 6). A prominent example concerns the binding energies of electrons in high-Z one-electron ions where the K-shell electrons are exposed to transient electric fields (e.g. 10^{16} V/cm in U^{91+}) close to the Schwinger limit. In a concerted effort and in close collaboration with the leading expert groups in theory, a comprehensive research program has been initiated to accomplish a significant validity check of non-perturbative bound-state quantum electrodynamics (QED) in regions $\alpha Z \approx 1$. Different experimental approaches will be applied (1s Lamb shift, 1s hyperfine structure, bound-state g-factor, mass measurements) thus probing QED at different mean-distances of the electron with respect to the nucleus. At the same time, highly precise atomic physics techniques will be applied as powerful tools for the determination of nuclear parameters such as nuclear radii and moments. Even high-precision determination of fundamental constants will be enabled.

At the high energy range, in particular FAIR will offer world-wide unique research opportunities to address a big variety of exciting topics. Here, highly-charged ions (HCI) can be stored and cooled

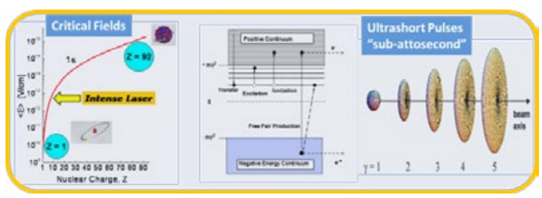


Figure 6: Left: electric field strength present for the ground-state electron in hydrogen-like systems as function of the nuclear charge. For comparison, typical field strengths provided by state-of-the-art high power lasers is also displayed. Middle: Dirac spectrum showing a variety of the atomic processes which can be studied in hitherto unexplored regimes. Right: electromagnetic field strength of a relativistic ion showing a strong enhancement in the transverse direction together with the compression in time.

at energies in the few-GeV/u range. These intense and high luminosity beams can then be coupled with dedicated internal multiphase targets as well as dedicated laser systems, including novel XUV, X-ray and high power lasers. This will enable us to explore a broad range of interesting physics phenomena. These include (among others):

- lepton pair-production in a nonperturbative regime;
- the negative continuum dielectronic recombination;
- radiative processes such as the radiative recombination and/or the radiative electron capture (REC) in up-to-now unexplored regimes;
- ionization dynamics and correlated electron motion induced by ultrafast extremely strong fields of relativistic ions;
- electron impact phenomena, such as excitation and ionization as well as the resonant coherent excitation process.

In addition, the coupling of various types of lasers with the ion beams in the high energy storage ring (HESR) would enable tests of bound-state quantum electrodynamics and the special theory of relativity with improved precision. Moreover, detailed experimental concepts have been worked out to explore parity non-conservation effects in highly charged ions and thus test the standard model.

Experiments at HESR at relativistic beam energies will be complemented by experiments at CRYRING and the HITRAP facilities at FAIR which focus on atomic and nuclear physics of exotic systems down to very low beam energies (< 10 MeV/u) and even at rest. Both CRYRING and HITRAP are coupled to the ESR which allows to decelerate ions from high energies (400 MeV/u) to the injection energy of both facilities providing in this way very-high Z ions in the bare or the few-electron state from a kinetic energy of 10 MeV/u continuously down to near- thermal energies. This scenario is worldwide unique and will e.g. deliver high-accuracy data for bound state QED (minimizing Doppler shifts) as well as the determination of fundamental constants. In addition, atomic collisions can be studied in the non-perturbative, adiabatic regime, even the electron dynamics in super-critical fields of transient super-heavy quasi-molecules will be accessible.

Furthermore, in the energy range of ~1-10 MeV/u the Fast Ion – Slow Ion Collisions (FISIC) project is planned and currently being developed at the S3 beamline of the SPIRAL2 facility. The project aims to utilize the intense ion beams provided by the SPIRAL2 facility to address the ion-ion collisions in the hitherto unexplored intermediate regime. Such studies are of fundamental interest as they will allow benchmarking the state-of-the-art atomic theories in the regime where most of the current standard approaches have not yet been applied. Furthermore, this regime is particularly interesting, because here cross sections for various atomic processes are of the same order of magnitude, the multiple processes become important and the ion stopping power is at maximum. Moreover, knowledge of the fundamental mechanisms at stake in the fast ion – slow ion collisions in atomic physics can provide a real breakthrough in the understanding of energy transfers in various plasmas such as inertial confinement fusion plasmas or stellar/interstellar plasmas. Indeed, ion-ion collisions are underlying many astrophysical phenomena in the universe but one of the least studied in laboratory. Here, it should be also mentioned that the low-energy branch of the FISIC experiment is generally mobile and can be transported and installed at CRYRING to extend the range of available ions into the high-Z range which would also be unique in many aspects.

Bunched FAIR beams of highest intensities provide huge energy densities (hundreds of kJ/g) and allow novel experiments and unprecedented diagnostic capabilities. Matter exposed to FAIR beams experiences similar extreme temperature and pressure conditions as prevailing in the interiors of stars, brown dwarfs or giant planets (so-called warm dense matter). The research program will focus on the equation of state and on transport properties of different materials in so far unexplored warm dense matter and high-energy density regions of the phase diagram. Related to these major goals, phase transitions, hydrodynamics and instabilities are of great interest. For instance, particle coupling in dense plasmas changes significantly, leading to different properties that need to be experimentally investigated (see Figure 7). Sophisticated computational tools have been developed to understand and predict the hydrodynamic processes of ion-beam heated matter. This allows to design special target configurations which enable a precise diagnostic of the target state with a minimum of measured quantities. State of the art optical and laser diagnostics will be applied to improve the understanding of atomic physics and thermodynamic properties of matter under these extreme conditions.

For the completion of the plasma physics research program at FAIR, the availability of a powerful probe (or driver) is essential. This probe can very advantageously be based on a high-energy laser that is matched to the requirements of experimental schemes, but also serve a much larger community within the FAIR research pillar APPA (Atomic Physics, Plasma Physics, and Applied Science). A

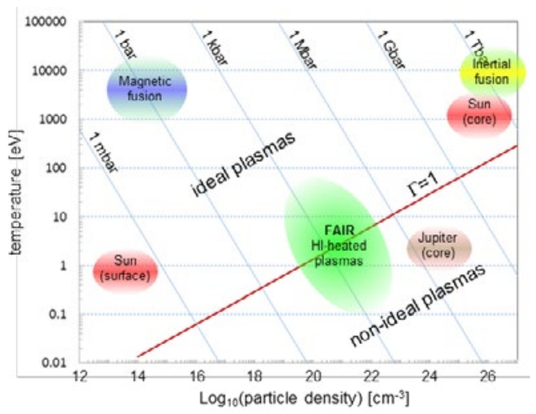


Figure 7: Schematic phase diagram showing the areas accessible with FAIR and other facilities as well as the conditions existing in cosmic objects. The red line separates the ideal and dense, strongly coupled plasma regimes (warm dense matter).

project to build this laser, the so-called "Helmholtz Beamline", exists on the roadmap of infrastructure of the Helmholtz society and is currently in the planning stage. During this stage GSI together with the Helmholtz center in Dresden Rossendorf and the Helmholtz Institute Jena are conducting the necessary R&D in the fields of laser technology and laser-based diagnostics at their facilities. This includes experimental demonstrations and validations at the PHELIX facility.

SUMMARY

Nuclear Physics is in the forefront of many applications which cover the range of the needs of Humanity in terms of energy, health, knowledge and protection. This is due to the peculiar properties of nuclear interactions with matter but also to the developments and the expertise developed by Nuclear Physics groups in accelerator technology, radiation detector technologies, high-performance computing, event reconstruction and 'big data'.

The main domains of applications have been reviewed in this chapter showing some important progresses and new orientations since the last Long Range Plan in 2010:

- In the nuclear energy domain, the safety of existing and future installations has become the main concern in the wake of the Fukushima accident. The main consequences are a need for accurate and predictive simulation codes based on reliable nuclear data.
- In the medical domain, the new theranostic approach leads to the development of adapted techniques for cancer treatment, in particular to the development of specific radio-isotopes, and more efficient imaging techniques. Thanks to the developments of high light-yield and fast scintillators coupled with high-performance computing Monte-Carlo codes the efficiency of diagnostics is improved and the dose to the patient can be reduced. Such developments should also permit to improve the detection techniques for nuclear security and counter terrorism.
- In the environmental domain, the global warming and urban pollution has become of main concern for our societies. Efficient low-energy accelerator-based techniques are used to trace aerosols and study their role and impact in these problematics.
- With the availability of high-intensity accelerators and new installations (GANIL-SPIRAL2, ESS, FAIR, HIE-Isolde, ELI-NP) new studies in material, atomic and plasma physics will be possible, exploring matter in extreme conditions. Some of these installations will also be used to study and develop the production of new radioisotopes for medical use.

Perspectives and needs

In the following we try to draw some needs for the future of Applied Nuclear Physics in Europe:

- *Maintain an adequate level of competence and expertise in the field of Applied Nuclear Physics.*

Applications of nuclear physics to energy, medicine, materials, space, security and environment are the fields with the largest expansion potential in nuclear physics. In this respect, training and education at all levels (Bachelor, Masters, PhD) of a new generation of researchers is fundamental. The activities in Nuclear Physics with applications should be promoted and the developments of novel accelerators and sensors for applications be pursued.

- *Strengthen the communication between Nuclear Physics community and end-users.*

The complexity of applied nuclear methods, the special infrastructure needed in applications and, most importantly, the necessary knowledge in nuclear physics often prevents other communities from applying nuclear methods. Applied Nuclear Physics communities could be encouraged to build networks offering their services to potential users that could be integrated in the emerging European Open Science Cloud.

- *Maintain a high level of expertise in nuclear data activities and support those related to* *the measurement, the evaluation and the dissemination of nuclear data in Europe.*

The compilation, evaluation and dissemination of nuclear data are laborious tasks that rely heavily on contributions from experts in both the basic and applied science research communities. Efforts carried out at national and international levels benefit from the coordination provided by international organisations such as the International Atomic Energy Agency (IAEA) in Vienna and the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA-OECD) in Paris. The development and maintenance of nuclear data libraries, and dissemination of nuclear data to various user communities constitute major goals of the international networks associated with these agencies: the Nuclear Reaction Data Centres Network (NRDC/IAEA), the Nuclear Structure and Decay Data evaluators (NSDD/IAEA), and NEA Data Bank. The challenge facing the nuclear research and applications communities is to ensure that the new measurements performed in the European facilities are incorporated promptly into the available databases and are therefore used in both reaction modelling and evaluations that are important for energy and non-energy applications.

- *Promote the access to large-scale facilities for applications, preserve and support small-size and dedicated installations.*

A key issue in Applied Nuclear Physics is to be able to perform innovative experiments, to test materials, detectors, etc. In this respect, the access to large-scale facilities for application experiments is important and should be preserved. On the other hand, due to the diversity of applications, local and dedicated small-size installations are needed, should be preserved and developed. In the particular case of radio-isotopes production for nuclear medicine or scientific applications it is important to maintain a network in Europe with different production facilities and different production methods. Radioactive targets require big efforts in production, chemical separation and purification as well as elaborated target manufacturing and handling. The strong support of target producing research groups will be a precondition for successful future experiments. Europe should strive for the establishment of a European Isotope Development Center matching the vigour of the US National Isotope Development Center.

NuPECC LRP2017 Town Meeting, Darmstadt January 11-13, 2017

Programme

Wednesday, January 11, 2017	**Thursday**, January 12, 2017	**Friday**, January 13, 2017
8:00-9:00 **Registration + Coffee**		
9:00-9:15 Welcome	**9:00-9:45** **(Chair: Adam Maj)** WG3: **Nuclear Structure & Reaction Dynamics** *Elias Khan, John Simpson*	**9:00-10:45** **(Chair: Jens J. Gaardhøje)** **International Context** NSAC: *Don Geesaman (25+5)* ANPhA: *Kazuhiro Tanaka (25+5)* CERN: *Eckhart Elsen (25+5)*
9:15-9:45 Outline LRP2017: *Angela Bracco*	**9:45-10:30** Discussion WG3	
	10:30-11:00 Coffee Break	10:45-11:15 Coffee Break
9:45-12:15 (Chair: Karlheinz Langanke) **Future Large-Scale Facilities** FAIR: *Paolo Giubellino (45+5)* EURISOL-DF Facilities: - Spiral2: *Navin Alahari (12+3)* - HIE-ISOLDE: *Maria Borge (12+3)* - SPES: *Gianfranco Prete (12+3)* EURISOL-DF: *Marek Lewitowicz (12+3)* ELI-NP: *Sydney Galès (15+5)* Dubna*: Mikhail Itkis (12+3)*	**11:00-11:45** **(Chair: Alex Murphy)** WG4: **Nuclear Astrophysics** *Gabriel Martinez Pinedo, Alison Laird*	**11:15-11:30 (Chair: Sotir. Harissopulos)** Introduction to Panel Discussion *Angela Bracco* **11:30-12:30** Panel discussion of overall recommendations, priorities & roadmap *LRP2017 Steering Committee*
	11:45-12:30 Discussion WG4	**12:30-12:45** Summary and Conclusion: Angela Bracco
12:15-13:45 Lunch	12:30-14:00 Lunch	
13:45-14:45 **(Chair: Faiçal Azaiez)** **European Context** ESFRI: *Giorgio Rossi (25+5)* ENSAR2: *Muhsin N. Harakeh (25+5)*	**14:00-14:45** **(Chair: Eberh. Widmann)** WG5: **Symmetries & Fundamental Interaction** *Klaus Kirch, Klaus Blaum*	
14:45-15:30 **(Chair: Bernd Krusche)** WG1: **Hadron Physics** *Diego Bettoni, Hartmut Wittig*		
15:30-16:15 Discussion WG1	**14:45-15:30** Discussion WG5	**https://indico.gsi.de/conferenceDisplay.py?confId=5177**
16:15-16:45 Coffee Break	15:30-16:00 Coffee Break	
16:45-17:30 **(Chair: Eugenio Nappi)** WG2: **Properties of Strong-Interaction Matter** *Silvia Masciocchi, François Gélis*	**16:00-16:45** **(Chair: Nicolas Alamanos)** WG6: **Applications & Societal Benefits** *Marco Durante, Alain Letourneau*	
17:30-18:15 Discussion WG2	**16:45-17:30** Discussion WG6	
18:15-20:00 **Welcome Reception**		

List of Acronyms and Abbreviations

AD	antiproton decelerator
AdS/CFT	anti-de Sitter/conformal field theory
ACTAR	active target
ADS	accelerator driven system
AGATA	Advanced GAmma Tracking Array
AGB	asymptotic giant branch
ALICE	A Large Ion Collider Experiment
ALP	axion-like particle
ALTO	Accélérateur Linéaire – Tandem Orsay
AMS	accelerator mass spectroscopy
ANC	asymptotic normalisation coefficient
ATLAS	particle physics experiment at LHC
BAU	baryon asymmetry of the universe
BBN	big-bang nucleosynthesis
BEC	Bose-Einstein condensate
BELLE	experiment at the KEK B-factory
BES	Beijing Spectrometer
BH	black hole
BM@N	baryonic matter at NICA
CBM	Condensed Baryonic Matter
CBRNE	chemical, biological, radiological, nuclear, explosives
CCB	Cyclotron Centre Bronowice
CCSN	core collapse supernova
CEA	Commissariat d'Energie Atomique
CEBAF	Continuous Electron Beam Accelerator Facility
CERN	Conseil Européen de Recherche Nucléaire
ChPT	chiral perturbation theory
CGC	colour glass condensate
CKM	Cabbibo-Kobayashi-Maskawa
CMB	cosmic microwave background
CME	coronal mass ejection
CMS	particle physics experiment at LHC
COMPASS	Common Muon Proton Apparatus for Structure and Spectroscopy
COSY	COoler Synchrotron
CRT	coincidence resolving time
CT	computer tomography
CUNA	Canfranc Underground Nuclear Astrophyics
CVC	conserved vector current
CW	continuous wave
DAΦNE	Double Annular Φ Factory for Nice Experiments
DESY	Deutsches Elektronensynchrotron
DFT	density functional theory
DIS	deep-inelastic scattering
DVCS	deeply virtual Compton scattering
DVMP	deep virtual meson production
DY	Drell-Yan
EBIT	electron beam ion trap
ECOS	European COnsortium on Stable beams
ECT*	European Centre for Theoretical studies in nuclear physics and related areas
EDF	energy density functional
EDM	electric dipole moment
EFT	effective field theory
EIC	electron ion collider
ELENA	extra low energy antiproton ring
ELI	Extreme Light Infrastructure
ELI-NP	Extreme Light Infrastructure – Nuclear Physics
ELSA	Electron Stretcher and Accelerator
EMMI	Extreme Matter Institute

ENSAR	European Nuclear Science and Applications Research
EoS	equation of state
ERA	European Research Area
ESA	European Space Agency
ESFRI	European Strategic Forum for Research Infrastructures
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EURADOS	EUropean RAdiation DOSimetry group
EURISOL	EURopean ISOL facility
EXL	Exotic nuclei studied with Electromagnetic and Light hadronic probes
EXOGAM	gamma detector at GANIL
FAIR	Facility for Antiproton and Ion Research
FAZIA	4π A and Z Identification Array
FCC	Future Circular Collider
FF	form factor
FLAIR	Facility for Low-energy Antiproton and Ion Research
FNAL	Fermi National Accelerator Laboratory
FOPI	4π detector at GSI
FP7	EU Framework Programme 7
FRM-II	Forschungsreaktor München II
FRS	FRagment Separator
GANIL	Grand Accélérateur National d'Ions Lourds
GDR	giant dipole resonance
GSI	Gesellschaft für SchwerIonenforschung
GSR	generalised special relativity
GEM	gas electron multiplier
GENCI	Grand Equipment National de Calcul Intensif
GPD	generalised parton distributions
GRB	gamma ray burst
GSI	Gesellschaft für Schwerionenforschung
γ-SF	gamma strength function
HADES	High Acceptance Di-Electron Spectrometer
HBT	Hanbury Brown-Twiss (interferometry analysis)
HD	hyperdeformed
HERA	Hadron-Elektron-Ring-Anlage
HERMES	HERA experiment for spin physics
HESR	High Energy Storage Ring
HFS	hyperfine splitting
HIE-ISOLDE	high intensity and energy upgrade of ISOLDE
HIL	Heavy Ion Laboratory
HLbL	hadronic light-by-light
HQET	heavy quark effective theory
HPC	high performance computing
IA	integrated activity
IAEA	International Atomic Energy Agency
IAS	isobaric analogue state
IBA	ion beam analysis
IBER	Investigation on Biological Effects of Radiation
ICP	inductively coupled plasma
IFMIF	International Fusion Materials Irradiation Facility
IFMIF-DONES	IFMIF - DEMO-Oriented Neutron Source
IGISOL	ion guide isotope separation on-line
ILL	Institut von Laue – Langevin
IMR	intermediate mass region
INFN	Istituto Nazionale di Fisica Nucleare
INDRA	4π charged product detection array at GANIL
INT	Institute for Nuclear Theory
IN2P3	Institut National de Physique Nucléaire et de Physique des Particules
ISGDR	isoscalar giant dipole resonance
ISGMR	isoscalar giant monopole resonance
ISOL	isotope separation on-line

ISOLDE	ion separator on-line at CERN
ISOL@MYRRHA	isotope separation on-line at MYRRHA
ITER	International Thermonuclear Experimental Reactor
IUPAP	International Union of Pure and Applied Physics
J-PARC	Japan Proton Accelerator Research Complex
JEDI	Jülich Electric Dipole moment Investigations
JINA	Joint Institute for Nuclear Astrophysics
JINR	Joint Institute for Nuclear Research
JLab	Thomas Jefferson National Accelerator Facility
JRA	joint research activity
JSC	Jülich Supercomputing Centre
JYFL	University of Jyväskylä
KVI	Kernfysisch Versneller Instituut
LABEC	Laboratorio di Tecniche Nucleari per I Beni Culturali
LAND	Large Area Neutron Detector
LBE	lead-bismuth eutectic
LCB	laser Compton backscattering
LEAR	low energy antiproton ring
LET	linear energy transfer
LFV	lepton-flavour violation
LIGO	Laser Interferometer Gravitational-Wave Observatory
LINAG	liner accelerator at GANIL
LHC	Large Hadron Collider
LHCb	detector at LHC
LMR	low mass region
LNGS	Laboratory Nazionali di Gran Sasso
LNF	Laboratori Nazionali di Frascati
LNL	Laboratori Nazionali di Legnaro
LNS	Laboratori Nazionali del Sud
LUNA	Laboratory Underground for Nuclear Astrophysics
MAMI	Mainz Mikrotron
MARA	Mass Analysing Recoil Apparatus
MAYA	gas-filled active target detection system at GANIL
MC	Monte Carlo
MEGAPIE	Mega Ampere Generator for Plasma Implosion Experiments
MEIS	medium-energy ion scattering
MELODI	Multidisciplinary European Low Dose Initiative
MPGD	micro-pattern gas detectors
MRI	magnetic resonance imaging
MRT	magnetic resonance tomography
MWPC	multi-wire proportional counter
MYRRHA	multi-purpose research reactor for high-tech applications
µSR	muon spin resonance / rotation
NA	nuclear astrophysics
NA60	North Area, CERN, Experiment 60
NFS	neutrons for science
NICA	Nuclotron-based Ion Collider fAcility
NLD	nuclear level density
NLO	next-to-leading order
NRF	nuclear resonance fluorescence
NS-BH	neutron star – black hole
NS-NS	double neutron star
NSCL	National Superconducting Cyclotron Laboratory
n_TOF	neutron time-of-flight facility
NuSTAR	Nuclear Structure, Astrophysics and Reactions
PAC	perturbed angular correlation
PANDA	antiProton ANnihilation at DArmstadt
PDF	parton distribution function
PDR	pygmy dipole resonance
PEP	Pauli exclusion principle
PERC	proton and electron radiation channel

PES	potential energy surface
PET	positron emission tomography
PETRA	Positron-Elektron-Tandem-Ring-Anlage
PIGE	proton induced gamma emission
PIXE	proton induced x-ray emission
PM	particulate matter
PSI	Paul-Scherrer-Institut
PSP	permutation-symmetry postulate
QCD	quantum chromodynamics
QED	quantum electrodynamics
QFT	quantum field theory
QGP	quark gluon plasma
RBS	Rutherford back scattering
R^3B	Reactions with Relativistic Radioactive Beams
RBE	relative biological effectiveness
REC	radiative electron capture
RGM	resonating group method
RHIC	Relativistic Heavy Ion Collider
RI	research infrastructure
RIB	radioactive ion beam
RICH	ring imaging Cherenkov counter
RPA	random pressure acceleration
RTG	Radioisotope Thermoelectric Generator
SBBN	standard big bang nucleosynthesis
SD	superdeformed
S-DALINAC	Supraleitender Darmstädter Elektronenlinearbeschleuniger
SF	spectroscopic factor
SHE	superheavy elements
SHM	statistical hadronisation model
SIB	stable ion beam
SIDIS	semi-inclusive deep-inelastic scattering
SIDDHARTA	Silicon Drift Detector for Hadronic Atoms Research by Timing Application
SIMS	secondary-ion mass spectrometry
SIS	SchwerIonen Synchrotron
SM	standard model / shell model
SMEFT	Standard Model Effctive Field Theory
SMF	stochastic mean field
SMMC	shell-model Monte Carlo
SN	supernova
SPECT	single-photon emission computerized tomography
SPES	Selective Production of Exotic Species
SPIRAL	Système de Production d'Ions Radioactifs Accélérés en Ligne
SPS	Super Proton Synchrotron
SRA	Strategic Research Agency
SST	spin-statistics theorem
STEM	science, technology, engineering, mathematics
SUSY	supersymmetry
TALENT	Training in Advanced Low-Energy Nuclear Theory
TAS	total absorption spectroscopy
TGCC	Très Grand Centre de calcul du CEA
THM	Trojan horse method
TMD	transverse momentum dependent distribution function
TNA	transnational access
TPC	time projection chamber
TOF	time of flight
UNILAC	Universal Linear Accelerator (at GSI)
VAMOS	versatile spectrometer at GANIL
WEP	weak equivalence principle
WIMP	weakly interacting massive particle
WLCG	Worldwide LHC Computing Grid

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