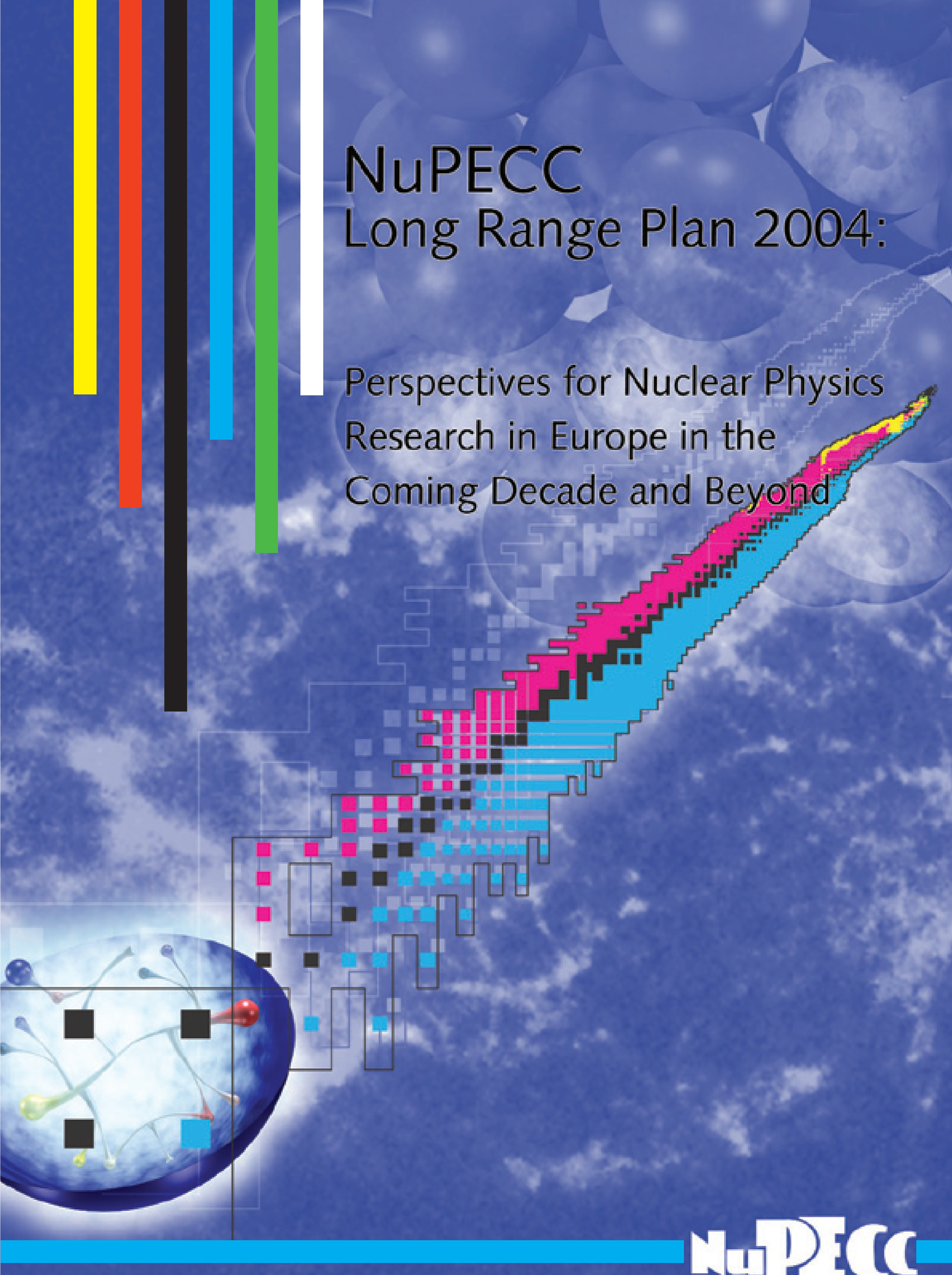
NuPECC
Long Range Plan 2004:

Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond



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NuPECC Long Range Plan 2004:

Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond

edited by:

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NuPECC is an Expert Committee of the European Science Foundation

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(an Expert Committee of the European Science Foundation)

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[1] † (7. September 2003)

Preamble

With this document NuPECC, the Nuclear Physics European Collaboration Committee, presents its Long Range Plan 2004. NuPECC, an Expert Committee of ESF, is “to provide advice and make recommendations to the ESF and to other bodies on the development, organisation, and support of European nuclear research and of particular projects.” To this aim, NuPECC has in the past produced two long-range plans (LRPs). The first LRP was published by NuPECC in November 1991, the second in December 1997.

NuPECC in its December 2001 meeting in Vienna, Austria, initiated the process for the LRP 2004. It defined the subfields of nuclear physics to be addressed and established Working Groups spanning the areas of nuclear physics and its application: Nuclear Structure, Phases of Nuclear Matter, Quantum Chromodynamics (QCD), Nuclear Physics in the Universe, and Fundamental Interactions and Applications.

Conveners and two liaison members of NuPECC were assigned to each Working Group. 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. The reports were to be integrated into a single report with the specific objectives: i) to provide the community and the funding agencies with a coherent picture and advice on the whole field, ii) to make optimum use of existing and future research infrastructures (RIs), and iii) to select the crucial experiments. This broad and intensive effort should lead to a report that provides guidance for nuclear science in Europe for about the next decade.

A Town Meeting to discuss the NuPECC LRP was held at GSI, Darmstadt, from January 30 to February 1, 2003. Preceding the Town Meeting, preliminary reports of the Working Groups were posted on the NuPECC website. The Town Meeting was attended by around 300 participants, including many young scientists. The programme contained sessions on planned new facilities and upgrades of existing ones, reports by the conveners of the Working Groups, and also presentations of ideas not covered in these reports. The Town Meeting concluded with a general session to discuss the NuPECC recommendations, distilled from the priorities defined by the various groups for their own subfields.

Following the Town Meeting, NuPECC discussed and finalized the recommendations in subsequent meetings in 2003. During this period, the conveners 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 2004: Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond”.

The report starts with an Executive Summary chapter on the general trends and the exciting ideas of modern nuclear physics, followed by the set of recommendations and priorities. The various reports of the Working Groups follow in the order: Quantum Chromodynamics (QCD), Phases of Nuclear Matter, Nuclear Structure, Nuclear Physics in the Universe, Fundamental Interactions and Applications.

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. 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 which go beyond the capabilities of an individual country.

Contents

1. Executive Summary

The temperatures here on Earth and the energies reached in most of the Universe surrounding us are much lower than the typical energy scale of QCD, the basic theory of the strong interaction. We therefore normally meet strongly interacting matter in the shape of atomic nuclei, built out of quarks that are "frozen" into nucleons, i.e. protons and neutrons. There are typically many nucleons in a nucleus, the heaviest nuclei known today have almost 300 nucleons, and the multitude of quantum states that are possible explains the rich variety of phenomena that is observed. It is the task of nuclear physics to unravel this myriad of quantum structures and to find the ordering principles that hold in nucleons and nuclei.

The various chapters in this report on the NuPECC Long-Range Plan (LRP) consider the achievements and developments made in the subfields of Nuclear Physics in the last decade and reflect on the issues that need to be addressed in the coming one. The working groups that have written these chapters, after consultation with colleagues in the field, also formulated a set of recommendations for the subfields concerned. These in turn formed the basis for NuPECC's recommendations, which are given at the end of this executive summary.

The chapters of this report have been written for the experts in the field. In this executive summary, effort is made to provide an overview for policymakers and scientists in other fields. The presentation of the various subfields follows the same sequence as that of the chapters in the main report and does not reflect any priority.

Quantum Chromodynamics

The physics of hadrons and nuclei is the physics of the strong force. The theory of the strong interaction, Quantum Chromodynamics (QCD), is remarkably successful in describing high-energy experiments involving quarks and gluons. The application of QCD to the lower energies (and longer distance scales such as the size of the atomic nucleus) is a major challenge. The rapidly increasing strength of the interaction at low energies makes it impossible to apply perturbative techniques. However, the situation has improved considerably in recent years due to several theoretical developments. As a result, various QCD-based predictions are now available in the non-perturbative domain, which can be tested experimentally in the coming decade. Steps can now be made towards the realisation of a long-standing objective of nuclear physics, i.e. to understand the properties of nucleons and their mutual interactions (and how both act inside nuclei) in terms of the underlying theory of the strong interaction, QCD.

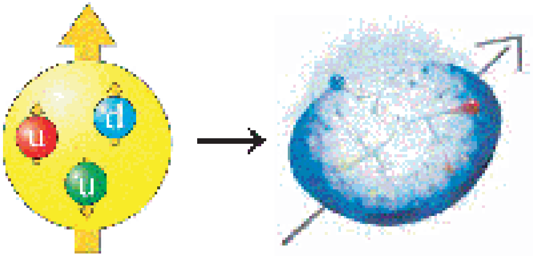

Figure 1.1: The evolution of our understanding of the structure of the nucleon. In the naive model of the 80-ies (left picture), the nucleon was assumed to consist of two up-quarks and one down-quark only. At present the nucleon is known to have a rich vacuum structure as well, containing a large number of virtual quark-antiquark pairs and gluons.

The mass of the u and d quarks in the proton (and other hadrons) is surprisingly small ($\sim$ 10 MeV) as compared to the mass of the proton itself (938 MeV). This gives rise to an approximate symmetry of QCD, known as chiral symmetry, which would be exact if the quark masses were zero. This symmetry is spontaneously broken at low energy and momentum scale. Pions, the well-known carriers of the long-range nuclear force, are the corresponding Goldstone bosons. They constitute the basic elements of the effective field theory, which represents QCD at large distance scales. Its systematic low-energy expansion is known as chiral perturbation theory, which has been tested successfully in the description of a variety of low-energy processes involving pions, including high-precision experiments in the area of meson photo-production and Compton scattering on nucleons.

Spontaneous chiral-symmetry breaking is reflected in the spectrum of hadron masses which displays a characteristic gap. Insight into the physical mechanisms which govern this mass gap can be gained from studies of changes of such spectra in nuclear systems. Detailed analysis of high-energy heavy-ion reactions as well as high precision measurements of low-energy meson-nuclear states can shed light on this.

Large-scale simulations of QCD on four-dimensional space-time lattices, a technique known as 'lattice-QCD', can be used to solve QCD problems involving low energies and/or large distance scales. Linking the results of such simulations to actual experimental observables still requires major steps. Improved analytical methods for removing artefacts of discretisation and extrapolations using effective field theory methods, together with steadily increasing computer power will make the presently available lattice-QCD results much more realistic. Decisive breakthroughs are expected in the near future.

A third development is the introduction of the so-called generalised parton distributions (GPDs), which present a unified framework to describe a whole range of (mostly exclusive) reactions. The GPDs are a generalisation of the usual parton distributions describing the momentum or helicity distributions of the quarks in the nucleon. The GPDs are also sensitive to quark-quark momentum correlations and quark-antiquark configurations in the nucleon. Hence, the GPDs provide information on nucleon properties that is otherwise hard to access. The most prominent example is the total angular momentum carried by the quarks in the nucleon, which can be obtained from an integral over a certain combination of GPDs. It has been shown theoretically that the amplitudes for various reactions factorise in a (calculable) hard-scattering part and a combination of such GPDs if the momentum transfer involved is sufficiently high. This proof makes it possible to extract GPDs from experimental data, and the GPDs thus offer a new unified interface for comparing experimental data and the results of non-perturbative QCD calculations.

More explicitly, these developments have led to the following QCD-based predictions, which need to be experimentally investigated:

- Hadron spectroscopy: according to QCD it should be possible to form gluon-rich hadrons, i.e. glue balls. Similarly, hybrid states composed of a combination of quarks and gluonic excitations should exist. The existence of such states represents a hard QCD prediction[1].
- Quark dynamics: from both lattice QCD and first exploratory experimental data there is growing evidence for a large gluon polarisation in the nucleon, a possibly large but oppositely oriented quark orbital angular momentum, and a large transverse quark polarisation. Moreover, it is expected that the momentum dependence of the single unmeasured (relatively large) quark distribution function, the transverse-spin distribution, is much weaker than that of the well-known unpolarised quark distributions.

Apart from these two key areas of future re-

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[1] When this review was finished first indications of "exotic" narrow hadronic states in the mass range between 1.5 and 3.5 GeV have been reported. While one of those states can most likely be associated with a new charmed meson (D^*_{sJ}) and another one with a new charmed baryon (Ξ^+_{cc}), there are speculations that another one of these narrow states represents a so-called pentaquark state with a dominant($uudd\bar{s}$) configuration. Further work is needed to verify these claims.

search, many more QCD-based experiments are foreseen in the coming years. These include measurements of modifications of hadron properties in nuclear systems, studying the role of strangeness in meson-threshold production, the search for missing resonances in the baryon mass spectrum, measurements of quark energy loss in matter, the search for colour transparency, and the implantation of strange or charm quarks in nuclei as a novel probe of nuclear structure.

In the coming decade Europe is in a unique position to play a leading role in the quantitative exploration of non-perturbative QCD because of the availability of a range of highly competitive experimental set-ups that will make it possible to address each of the aforementioned issues:

- At the recently approved international Facility for Antiproton and Ion Research (FAIR) at the GSI laboratory in Darmstadt, the PANDA experiment (which will be installed at the HESR ring at GSI) will be in a unique position to search for the existence of glue balls, hybrids and novel charm quark states. The use of an antiproton beam and the chosen energy enables the exploration of states of all possible quantum numbers in a mass domain populated by only very few known states.
- The HERMES experiment at DESY, and the COMPASS experiment at CERN have started a new series of deep-inelastic scattering experiments at low and high Q^2 values, which are expected to yield first measurements of the gluon polarisation, the nucleon transverse spin distribution, and the generalised parton distributions.

Apart from these experiments, the MAMI-C facility in Mainz, which is presently under construction, will further explore the low-mass baryon spectrum and chiral perturbation theory, while the DAΦNE facility in Frascati will study (hyper-)nuclei containing strange quarks.

On a longer time-scale the full exploration of the non-perturbative QCD sector requires the construction of a high-intensity, high-energy lepton scattering facility. The high-intensity is crucial in order to obtain sufficiently precise data on the nucleon transverse-spin distribution, and the quark orbital angular momentum to be decisive when comparing these data to novel QCD predictions. The construction of such a facility requires international worldwide collaboration.

The Phases of Nuclear Matter

Nuclei comprise more than 99% of the mass of the directly observed matter in the universe. Yet nuclei, lying at the centre of atoms, occupy only about one quadrillionth of the volume of normal matter, which tells us they have a density beyond everything we may meet in our normal world. But nuclei are not the only manifestation - though a very important one - of nuclear matter. They represent nuclear matter in the (cold) ground state, with the density following from the general characteristics of the short-range nature of the strong interaction. This state of matter is expected to exist in a macroscopically extended form in neutron stars at up to several times the density of nuclei. At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons of nuclear matter may form a new state of matter, which is colour-superconducting (where ‘colour’ represents, in the language of the strong force, a quantum property of the quark rather than a ‘true’ colour).

Beyond compressing (or expanding) cold nuclear matter, it can be heated by pumping energy into it. We therefore speak of the temperatures of nuclear matter. These can reach values unimaginable for our daily world but represent the state of matter as it existed during the first fractions of a second of the universe; or in the so-called quark-gluon plasma, i.e. matter where the usual behaviour of quarks in hadrons is no longer valid and important symmetries for fundamental matter are fully restored. Transitions from one regime of nuclear matter to another regime involve fundamental changes in its bulk behaviour and proceed through phase transitions of various nature.

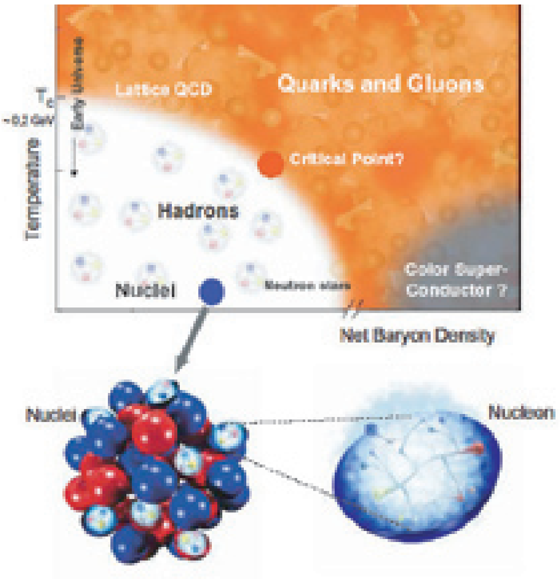


Figure 1.2: A schematic diagram illustrating the various phases of nuclear and hadronic matter. Nuclei, which behave like liquid, will undergo a phase transition to gas of nucleons at relatively low temperatures where the nucleons keep their identity. At very high temperatures, a transition to a quark-gluon plasma phase should occur like existed in the very early universe. Another possible intriguing phase of matter could occur at very high density where nucleons melt and colour superconductivity prevails.

Figure 1.2 summarises the ranges of temperature versus density that nuclear matter may exist in. At densities lower than those inside normal atomic nuclei, nuclear matter should undergo a transition from a liquid to a gaseous phase. This phase transition should occur at a temperature of about 10^{11} K or 15 MeV. Just as in an ordinary liquid like water, the nuclear-matter phase change should occur at a constant temperature if the pressure is not varied. During the transition, nuclear matter exists as a mixture of the liquid and gaseous states. Density fluctuations should occur in this mixed phase, varying the abundances of nuclear droplets - small nuclei with 6 to 50 nucleons - that are produced. Unlike the case of ordinary liquids, however, quantum mechanics plays an important role in nuclear matter and its phase transitions.

The nuclear liquid-gas phase transition can be studied in the laboratory by observing the disassembly of the finite nuclear systems produced by colliding atomic nuclei at accelerator facilities. Experiments measure the probability of decay of the excited system into multiple light nuclear fragments, or droplets of nuclear liquid. Typical beam energies range from 1 to several times the Fermi energy of nucleons in nuclei. Experiments have been devised to measure all fragments, and to distinguish between the simultaneous fragment emission expected from a phase transition and evaporation of nuclei with 5 to 60 nucleons over a longer time scale from the surface of larger nuclei. Identifying those collisions where bulk multifragmentation occurs is expected to allow extraction of the thermodynamic properties of nuclear matter at the liquid-gas phase transition. These processes in charge-asymmetric ion collisions have already revealed new interesting isospin dynamics effects, from isospin distillation to isospin diffusion, that are very effective for the production of exotic unstable elements and are, moreover, very sensitive to the poorly known in-medium nucleon-nucleon interaction in the isovector channel.

Relativistic heavy-ion collisions at much higher energies open a window to study matter at the highest energy and matter densities. The collisions, previously at the SPS (CERN), now at RHIC (Brookhaven) with ten times, and in the near future at the LHC (CERN) with hundred times the SPS energies, produce large regions of matter at unprecedented energy densities in the laboratory. Conversely, a project with focus on the exploration of nuclear matter at the highest matter densities that can be achieved in heavy-ion collisions, is the new facility planned for GSI (Darmstadt). It builds on the pioneering experiments at lower energy at the Bevalac (Berkeley) and SIS 18 (Darmstadt), and at the AGS (Brookhaven) but employing important new sensitive probes.

One of the new phenomena expected in this overall regime is the deconfinement of quarks. At low energies the quarks that make up neutrons, protons, and other hadrons are always confined in groups of two or three. At RHIC and the LHC such high energy densities will be created that the quarks and gluons are expected to become deconfined across a volume that is large compared to that of a hadron. By determining the conditions for deconfinement, experiments will play a crucial role in understanding the basic nature of confinement and shed light on how quantum-chromodynamics (QCD), the theory of the strong interaction, describes the matter of the real world. When nuclear matter is sufficiently excited by compression or heating, or both, the quarks should no longer be bound together, but should be able to move freely through the excited volume. Matter is believed to have existed in this form, a quark-gluon plasma, for the first few microseconds after the Big Bang. The nature of this confinement, which is a crucial aspect of the quark-gluon description of matter, is inadequately understood.

An exciting theoretical challenge in studying high-energy-density matter is to understand chiral symmetry. Massless quarks possess a handedness (i.e., right-handed or left-handed); this chirality is a fundamental symmetry of QCD. In the everyday world, particles have mass and chiral symmetry is not exactly preserved. How the massless quarks turn into particles with mass is not completely understood, but the process spontaneously violates the chiral symmetry of QCD. By probing the transition between states where chiral symmetry holds and where it is broken, insight can be gained about how particles acquire their masses. Although the connection between chiral symmetry and quark deconfinement is not well understood at present, chiral symmetry is expected to hold in the quark-gluon plasma.

From the time of the Big Bang, the early universe cooled as it expanded. For the first microseconds, the temperature was at least hundreds of MeV and matter existed as a quark-gluon plasma. Figure 1.2 indicates the evolution of the early universe as a downward trajectory practically along the vertical axis of the phase diagram. The matter of the early universe had a much smaller net number of baryons than photons, about one in a billion. As the universe cooled below the critical temperature for deconfinement, the primordial plasma coalesced into hadrons. The quarks found partners and became confined into nucleons and mesons and eventually into the nuclei we observe today. If the transition were first-order, droplets of hadrons formed in the middle of the plasma similar to the way water precipitates into rain drops.

Such density inhomogeneities could have enhanced the abundance of certain light chemical elements. They may even have led to formation of strange-quark-matter nuggets or planetary-mass black holes, which could account for some of the so-far-unobserved dark matter in the universe. If the transition is relatively slow cosmologically, then the hadron formation process could contribute to the entropy, or disorder, observed as the number of photons in the universe. These features of the universe depend on how the transition from the quark-gluon plasma to hadronic matter took place.

In neutron stars the properties of matter under extreme conditions also play a crucial role. For example, our present lack of knowledge of the properties of matter at densities beyond twice that of nuclei is reflected in an uncertainty about the maximum mass of neutron stars. Experiments, by providing information on the equation of state, should help us determine possible states of matter in neutron stars. For example, neutron stars may, at a density as low as a few times the nuclear-matter density, contain a mixed state consisting of droplets of quark matter immersed in ordinary hadronic matter fluid. If their central density rises to five to ten times that of nuclear matter, they may have quark-matter cores in their deep interiors. One cannot even definitely rule out, without further data, the possibility of a distinct family of quark stars with higher central densities than those of neutron stars.

The future facilities offer unique opportunities - the matter created in LHC collisions at thousands of GeV per nucleon will redefine the energy and temperature frontiers. The matter is expected to exist much longer than the hot matter studied in experiments to date. The studies at the future GSI facility will probe the density frontier and the regions of excited and compressed matter still composed of hadrons. The latter is expected to exist in a sustained fashion only at the high net-baryon density region, traversed in nucleus-nucleus collisions at intermediate energies of a few tens of GeV per nucleon.

Nuclear Structure

The task of explaining low-energy nuclear structure starting from QCD is a formidable one, and is best approached in steps: from the basic equations of QCD through effective field theories to nucleon-nucleon forces and further on to the many approaches used to describe nuclear structure, such as mean field models and shell models. The experimental information that has emerged during the last years on short-lived nuclei has in many important ways challenged the modelling and understanding built upon the stable nuclei: to a certain extent we are moving from a one-dimensional picture where the mass of a nucleus varies to a two-dimensional picture where both proton and neutron numbers vary over a wide range. This has revitalised the theoretical activities on a broad front.

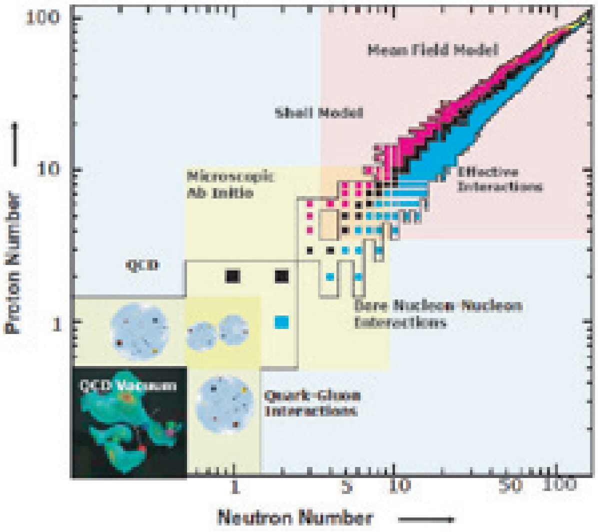


Figure 1.3: The chart of nuclei. Although QCD is the basic theory of strong interactions, other models must take over for a proper description of the low-energy nuclear behaviour. The figure indicates some models used and their region of applicability. Note that the regions overlap, we are progressing towards a complete understanding of nuclear structure.

Steady progress in theoretical techniques as well as in computational power allow us now to describe, exactly and microscopically, systems containing up to twelve nucleons starting from the basic two-body nucleon-nucleon (2N) and three-body (3N) forces. Beyond this, effective interactions must be used, but links between the basic forces and the effective ones are partially known and attempts to fully establish them constitute a crucial field of study now and in the future.

The important workhorses in nuclear-structure theory have been the interacting shell model at lower masses and mean-field theories at higher masses. The ongoing development has yielded important regions of overlap between these two different approaches. To extrapolate reliably to more exotic nuclear systems is still a challenge (e.g. it seems that one of our traditional "building blocks", the magic numbers, do change as we move around in the nuclear chart), but one that is met with increasing success. Models in which correlations are taken into account have an important role to play here.

Submitting the nucleus to extreme conditions is an important test of its understanding. Two important directions taken are to increase its rotation frequency — this triggers many interesting structural changes e.g. in its shape — and to heat it up, from the regime where one can follow the configurations and the dynamics of individual protons and neutrons in the nucleus to a regime where a statistical approach is more appropriate. The study of symmetries in nuclei and how these symmetries can be broken has given important guidelines to how to unify the large body of present knowledge.

New experimental possibilities have enlarged our ability to probe the low-energy structures, in particular by going towards more short-lived nuclei (nuclei with a larger imbalance between the number of neutrons and protons) but also by making possible studies of specific nuclei such as the ones with equal numbers of protons and neutrons. This has allowed us to outline regions for future research and to develop plans for new facilities and new equipment that in the coming decade will take us an important step further in our understanding of the atomic nucleus.

The ability to generate energetic beams of significant intensity gives access to a new dimension of nuclear structure research. Much of what we know about nuclei, their structure and dynamics, comes from nuclear reactions. Such reactions in turn requires beams of probing particles (such as leptons, protons, deuterons, helium nuclei and heavier probes) and targets of nuclei to be studied. This, in essence, has limited studies to about roughly 300 stable nuclei that exist around us. Inverting the reaction kinematics, i.e. having targets of the above probe particles (hydrogen, helium, etc.) and having the nuclei to be probed in form of a transient beam, allows to extend reaction studies, in principle, to the full range of nuclei that exist (not yet known, but probably around 6000), even if they live as short as seconds or milliseconds. Much of the present and future effort is thus directed to extending the range of availability of beams of short-lived nuclei, steadily increasing the known cases in the nuclear chart.

Our ability to cool, confine and store nuclei, be it either for looking at their ground-state properties and their mass or in order to prepare them for experiments at higher excitations, has improved drastically during the last years. Also, our ability to detect with increasing efficiency and angular resolution the radiations emitted from nuclei (gamma-rays, neutrons and charged particles) have increased so that the threshold for detectable phenomena is decreased significantly. That, added to accelerator developments such as the recent start-up of facilities where short-lived nuclei are accelerated from thermal energies up to about the Coulomb barrier, has increased the experimental possibilities for nuclear-structure studies.

Existing accelerators and instrumentation can in the near future form the basis for addressing the new frontiers in nuclear structure, but new large-scale investments will be needed for taking the next quantitative step. For production of a large variety of isotopically pure beams two approaches should be pursued simultaneously. The in-flight separation method will be taken an important step forward at the new facility FAIR at GSI and the isotope-separation on-line (ISOL) method will be developed further through R&D work aiming towards EURISOL, to be constructed in the next decade. This would significantly enhance the number of different nuclei that can be produced as well as their production rates and must be complemented by new instrumentation to make full use of the beams.

The European nuclear-structure community has a strong international record and is well-positioned for harvesting the successes of the future, but it will require continued support for the experimental groups and a strong effort both in nuclear-structure and in nuclear-reaction theory.

Nuclei in the Universe

Nuclear astrophysics has developed in the last twenty years into one of the most important subfields of ‘applied’ nuclear physics. It is a truly interdisciplinary field, concentrating on primordial and stellar nucleosynthesis, stellar evolution, and the interpretation of cataclysmic stellar events like novae and supernovae. It combines astronomical observation and astrophysical modelling with meteoritic anomaly research and with nuclear physics measurements and theory.

The field has been tremendously stimulated by recent developments in laboratory and observational techniques. The rapid increase in satellite observations of intense galactic gamma-sources, observation and analysis of isotopic and elemental abundances in deep convective Red Giant and Asymptotic Giant Branch (AGB) stars, and abundance and dynamical studies of nova ejecta and supernova remnants allow the placement of stringent limits on the various stellar and nucleosynthesis models. The latest developments in modelling stars, novae, X-ray bursters, and supernovae allow now much better predictions from nucleosynthesis calculations to be compared with the observational data.

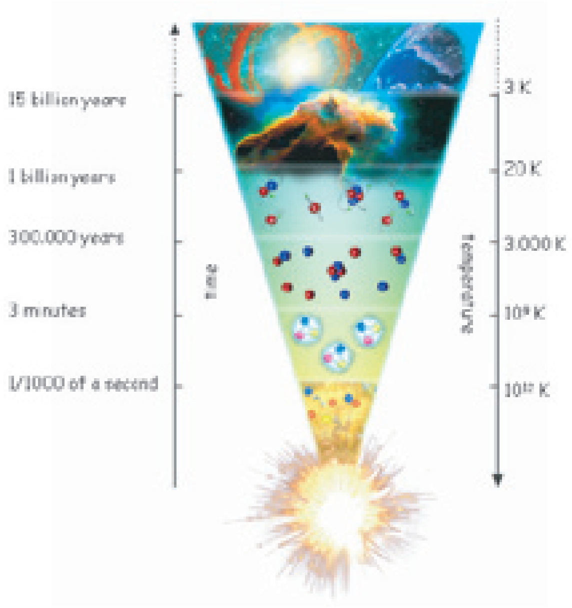


Figure 1.4: Nuclear physics does play a pivotal role during the different stages in the evolution of our universe. In the field of nuclear astrophysics, basic questions such as the origin of the chemical elements and the energy in stars are addressed. The answers do rely heavily on experimental information on the structure of stable and exotic nuclei and where this information is not available on theoretical models.

New spectroscopic capabilities have become available on the Hubble Space Telescope, and through new large telescope facilities like the VLT and the Keck. Highlights with significant public attention were the high redshift supernova search and its implication for the structure and dynamics of the Universe as well as the proof of oscillations for solar neutrinos on their way from the solar core to earth by earthbound detectors.

This solution to the solar neutrino puzzle does not only open the door to new physics beyond the Standard Model of particle physics, it also confirms the predictions of the solar models including their nuclear-physics input. The latter included the measurement of the ^{3}He(^{3}He,2p)^{4}He reaction cross section at the Gran Sasso low-energy underground facility. This milestone of nuclear astrophysics constitutes the first direct measurement of a reaction rate at stellar energies. To optimally exploit this unique facility, the installation of a compact high-current 5-MV accelerator, equipped with a highly-efficient Ge detector array is urgently needed.

Other highlights of experimental nuclear astrophysics include the development and successful use of novel neutron-time-of-flight facilities at Los Alamos and CERN, which allow to determine neutron-capture cross sections for the s-process with unprecedented precision, the high-accuracy mass measurements of many unstable nuclei at GSI, ISOLDE and GANIL, the determination of more than 30 new half-lives for neutron-rich nuclei on the r-process path, and the precision measurements of spin-isospin responses in nuclei at KVI, Groningen and RCNP, Osaka, which are important inputs in supernova simulations and for supernova neutrino detectors.

A new era of nuclear astrophysics has started with the use of radioactive ion-beam accelerators dedicated to the measurement of astrophysically relevant nuclear reactions involving short-lived nuclides. This field has been pioneered by the Louvain-la-Neuve facility, where several important low-energy nuclear reactions for explosive astrophysical environments have been studied in the last 10 years. New installations are now operational at Louvain-la-Neuve, TRIUMF, GANIL and at CERN. They will allow to determine some of the most important reaction rates for the nuclear networks in novae and X-ray bursters. Immediate upgrades of the existing facilities in Europe are crucial to bridge the gap until the second-generation radioactive ion-beam facilities become operational. This next generation of radioactive ion-beam facilities, planned and proposed in Europe (GSI and EURISOL), in Japan and in the USA, will then allow to produce and experiment with most of the astrophysically important short-lived nuclides, promising to remove the most crucial ambiguities in nuclear astrophysics arising from nuclear-physics input.

In many of the astrophysical models, nuclear theory has to bridge the gap between experimental data and astrophysical applications. Here, we clearly stand at the eve of a new era as the required step can now be taken on the basis of first-principle theoretical models rather than by empirical parameterisation of the data. This should reduce the uncertainties connected with the extrapolations into yet unexplored parts of the nuclear chart in the near future, thus going timely hand-in-hand with the experimental developments.

Nuclear astrophysics has benefited enormously from the progress in astronomical observation, astrophysical modelling and nuclear physics. However, many fundamental questions remain open. Given the unique interdisciplinary nature of the field, a global understanding can only be achieved by combined and coordinated efforts in the three subfields. Clearly, nuclear physics plays a central role in this endeavour.

Fundamental Interactions

Symmetries play an essential role in physics. While global symmetries give rise to conservation laws, local symmetries manifest themselves via forces. Four fundamental interactions are known: gravitation, weak interaction, electromagnetism and strong interaction. The Standard Model (SM) provides a coherent picture with astounding precision of the electromagnetic, weak and strong interactions. To find a unified quantum field theory for all fundamental interactions as well as to investigate the limits of and possibly physics beyond the Standard Model are central goals of current physics research. Due to the importance of fundamental interactions the associated questions are addressed by several subfields of physics. Nuclear-physics experiments and in particular nuclear-physics techniques play a crucial role in this challenging part of physics.

The Standard Model is based on two families of fundamental Fermions, i.e. leptons and quarks, each consisting of three generations. Forces are mediated by bosons, i.e. the photon, $W^{\pm}$- and Z^0-bosons, and eight gluons. Hadrons, the central objects of nuclear physics, are composed of quarks and gluons and are affected by all fundamental interactions. Within the Standard Model conservation of baryon number and conservation of several lepton numbers are observed. In addition weak interactions mix the quark flavours as described by the Cabbibo-Kobayashi-Maskawa (CKM) matrix. Recent experiments indicate that for leptons a similar mixing exists in the neutrino sector. The latter is strongly related with the search for finite masses of neutrinos, which will have a significant impact on cosmology as well as on our understanding of the structure of matter.

Among the fundamental forces the electroweak part of the Standard Model is best understood and can be evaluated with extremely high precision. In particular Quantum Electrodynamics (QED) is the best tested quantum field theory. Therefore, making use of the interference between electromagnetism, weak and strong interactions in specific nuclei and exotic systems allows for an improved description of the other interactions. Apart from the quantitative aspect, the theoretical descriptions of QED-based quantities are of high predictive power. Any deviation from the expectation represents a potential hint to new physics beyond the Standard Model and provides criteria for the validity of proposed speculative extensions to the Standard Model.

The Standard Model has a large number of free parameters, which have to be extracted from experiment. Among the most intriguing open questions are the hierarchy of the fundamental fermion masses, the number of particle generations, as well as the physical origin of the observed breaking of discrete symmetries, i.e. parity (P), time-reversal invariance (T) and combined charge conjugation and parity (CP), in weak-interaction processes. Specifically, the searches for additional sources of CP-violation are of great interest because they may relate to the observed matter-antimatter asymmetry in the universe. Although several related experimental facts, e.g. parity violation, can be well described within the Standard Model, the addressed questions exceed the present standard theory and are subject of speculative models such as supersymmetry, supergravity, string theory and others. There are attempts via dedicated nuclear- and hadron-physics experiments

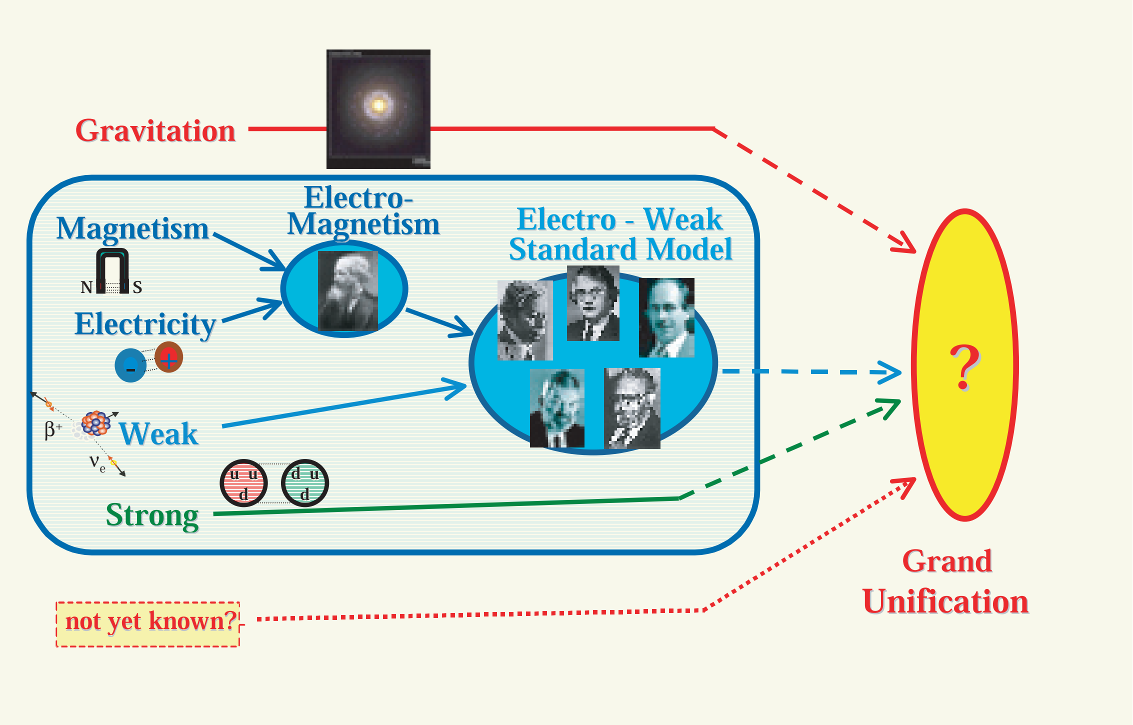


Figure 1.5: The standard model provides a coherent description of electro-magnetic, weak and strong forces. It is a central goal in theoretical physics to include also gravitation in a grand unification model. All observed fundamental forces would then be different low energy consequences of one single underlying interaction. Nuclear physics offers a number of possibilities to search for yet unknown interactions, which have been proposed to explain some of the features introduced "by hand" into the standard model. Such research is complementary to attempts in high energy physics and has in some cases even a higher discovery potential. (Photos ©The Nobel Foundation)

to shed some light on this speculative sector and to provide selection criteria between the models.

The research on *Fundamental Interactions* is rather diversified and is part of several subfields of physics. Taking advantage of recent developments in atomic, nuclear, neutron and particle physics remarkable progress could be achieved in several aspects. In the following only a selection of the most recent results and envisaged developments related to nuclear physics are listed:

- *Properties of neutrinos:* There exists now clear evidence for transformations of flavour. The most likely explanation are *neutrino oscillations* which are related to the difference of the squared neutrino masses, $\Delta m_{ij}^2 = |m^2(\nu_i) - m^2(\nu_j)|$. The new solar neutrino experiments KamLAND in Japan and BOREXINO in Gran Sasso National Laboratory, Italy should restrict the Δm^2-values. For a direct observation of oscillations, dedicated reactor neutrino experiments with a baseline of about 20 km will be necessary.

  Recent electron-neutrino mass measurements report an upper limit of $m(\nu_e) \leq 2.2$ eV. An improvement of this bound by one order of magnitude is envisaged by the proposed Karlsruhe Tritium Neutrino Experiment (KATRIN). A similar improvement on a slightly different effective mass as well as a clarification of the nature of the neutrino as a Dirac or Majorana particle is also expected from the proposed experiments of the next generation on neutrinoless double β-decay, i.e. CUORE and GENIUS in Europe, the American Majorana experiment and the EXO-experiment in Japan.

- *Time-reversal and CP violation:* Searches for permanent electric dipole moments (EDM) for various particles (molecules, atoms, nucleons) have been performed with high precision, recently. Improved limits of these EDMs and further those of muons and neutrons can be achieved from novel experiments, e.g. at next generations *Ultracold Neutron Sources* presently in development.

  Complementary studies of T violation in measurements of correlations between observables of positrons and neutrinos in β-decay in several nuclear systems are currently in progress. However, improved limits are required and are the goal of forthcoming experiments at ILL (TRINE), at NIST (emiT) and at PSI. In addition, there are CPT-tests with antiprotons at AD ring of CERN (ASACUSA, ATHENA, A-TRAP).

- *Fundamental constants and exotic atoms:* High-precision Lamb-shift measurements on one-electron systems, like the hydrogen atom, the muonium and hydrogen-like heavier atoms, have provided stringent tests to QED and most accurate fundamental constants. The muon $g-2$ experiment presently in progress at Brookhaven National Laboratory represents a crucial effort to improve the precision of the magnetic anomaly. An unambiguous determination of its hadronic part and related conclusive hints on deficiencies of the Standard Model require still intense theory work.

  The good knowledge of QED allows the extraction of properties of the strong interaction via the study of exotic atoms. Here, the DIRAC experiment at CERN should be mentioned which measures the $\pi^+ - \pi^-$-system and delivers presently the first data. An investigation of kaonic hydrogen should provide a direct measure of the strangeness content of the proton and is currently conducted at the DAΦNE storage ring in Italy.

The progress in the field of *Fundamental Interactions* is strongly correlated with the advances in different subfields of physics. Several of these subfields would benefit from the availability of an intense proton driver in Europe with several MW beam energy. Such a machine can serve as a core of a neutrino factory, a muon factory, a neutron spallation source as well as a driver of an advanced ISOL facility.

Applications of nuclear physics

The topics of applied nuclear physics are so many that a comprehensive overview on all of them is a difficult task. The spheres of competence involved in the applications of nuclear physics are dramatically varied since they include disciplines that are far apart from each other, not only with respect to the issues addressed but also in terms of the conceptual approach to them. Indeed, they span from life sciences and medicine, to humanistic disciplines like art-history, history itself and archaeology, to environmental sciences, to other scientific disciplines and technological or industrial fields. They also include the fields of civil security and humanitarian problems like contraband detection, anti-terrorism and demining.

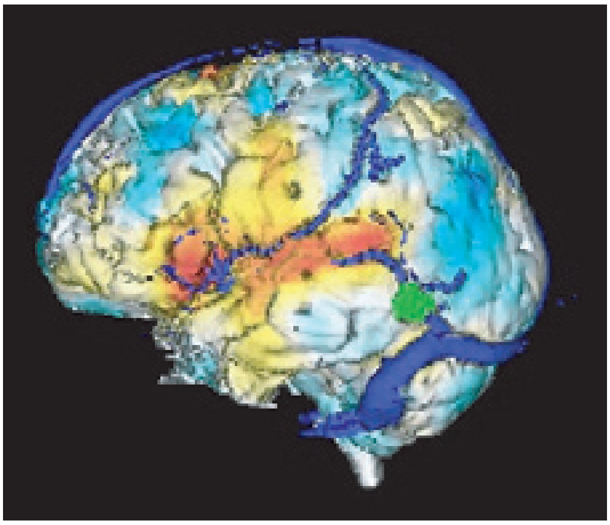


Figure 1.6: PET image of an active brain. The areas of high activity are depicted in red, the ones of low activity in blue.

About two years ago (November 2001), Nu-

PECC organised a meeting in Dourdan, France, entirely devoted to reviewing applications and interactions of nuclear physics. The main topics addressed were energy-related problems, life sciences and medicine, atomic and condensed matter physics. The presentations, ideas and discussions during this meeting were then collected in a report, recently published. We have therefore asked the convenors of the working groups of the Dourdan meeting to summarise the results thatemerged from the respective areas. These summaries are included as contributions to the present report. Concerning medical applications, another technique - not included in the Dourdan report - should be mentioned, Boron Neutron Capture Therapy of liver cancer. In a first case and an amazing surgical operation with the sequence of explant - neutron irradiation - reimplant of the liver, the technique proved to be effective in defeating a frequent form of secondary cancer with diffused metastases, otherwise with no hope of recovery.

Other important fields of application of nuclear physics remained completely to be addressed after the Dourdan meeting: in particular, environmental studies, archaeometrical applications, and the above-mentioned applications to multifaceted aspects of security and humanitarian problems.

Concerning environmental applications, important contributions from nuclear physics come from two groups of techniques, namely Accelerator Mass Spectrometry (AMS) and Ion Beam Analysis (IBA). The former opens a so-far undisclosed world in terms of capability to trace the evolution of crucial environmental processes, both natural and anthropogenic. For instance, our current predictions about changes in the environment (e.g. the climate) are working hypotheses at best, far away from solid theories with real predictive power. What is needed most are good data to back up model predictions, and AMS, through the combination of ultra-sensitive isotope detection with small sample sizes and high sample throughput, can make important contributions, providing a unique tool to trace large-scale movements of air and water masses. AMS has seemingly limitless applications, and in fact the steadily growing number of AMS facilities in Europe and in the world indicate the large demand for this technique. It is evident that there is a bright future ahead for this field.

Ion Beam Analysis can provide a further important tool for the environment, namely in the applications to studies of air and water pollution. For example, the association of clever sampling techniques for air pollutants with the combined use of several IBA techniques (PIXE, PIGE, elastic back- and forward-scattering) is a powerful means of monitoring air quality in urban and industrial areas. The multi-element capability of IBA makes it possible to reconstruct the sources of pollution through their characteristic emission fingerprint and time-behaviour.

As far as the applications of nuclear science for the Cultural Heritage are concerned, it is again AMS and IBA that play an important role. AMS finds its most popular application in the ^{14}C archaeological dating. Although this is a fascinating and still growing field, it is so well established already that no special emphasis will be given to it in this report. The progress of IBA for the investigation of materials and production technologies of ancient times is well illustrated in the experience of the dedicated accelerator laboratory at the Louvre. The range of discoveries about the past that this kind of investigation has produced - and its promises to further yield - is quite large.

Other developments deal with the societal and humanitarian applications of nuclear science. In addition to development of nuclear techniques for de-mining purposes there will a growing demand from the western world to develop techniques for the fight against terrorism. There is a strong need of surveillance and means of radiation protection in public sites. The development of advanced technologies will enhance the EC capabilities in the countermeasures to terrorist actions, improving the civil security and decreasing the risks connected to the use of weapons of mass destruction.

2. Recommendations and Priorities

Nuclear Science aims at the understanding of the structure, dynamics and overall properties of nuclear and hadronic systems. Nuclear Science also aims at the understanding of the universe from the first microseconds of its inception when the quark-gluon plasma (QGP) prevailed, through its history of star and galaxy formation where nuclear reactions play essential roles. Furthermore, Nuclear Science has applications that benefit society in many areas and has strong impact on other fields of science.

There have been major developments over the last decade in our understanding of the interaction between quarks mediated by gluons, as described in the framework of Quantum Chromodynamics (QCD). Furthermore, Lattice QCD has the potential of describing ground-state properties of hadrons. However, we are still far from describing the nucleon-nucleon interaction, and consequently nuclear structure and reaction dynamics in terms of the underlying quark structure. The development of the theoretical tools and the growing computing capabilities offer great promise to tackle these problems. New experimental facilities and advanced instrumentation are proposed to answer the challenging basic questions.

General recommendations Large investments in equipment and manpower have been made in the last decade. **NuPECC recommends the full exploitation of the existing and competitive lepton, proton, stable-isotope and radioactive-ion beam facilities and instrumentation.** In addition to the interesting physics results that will emerge, major beam-production development and detector R&D can be performed. These facilities will deliver the experimental capabilities in the coming 5 to 10 years and will serve as important training sites.

Furthermore, an extensive programme to investigate QGP in the framework of the large and active heavy-ion programme at LHC is foreseen with the ALICE experiment, which has been given very high priority in the last NuPECC LRP. **NuPECC strongly recommends the timely completion of the ALICE detector to allow early and full exploitation at the start of LHC.**

Many of the experiments and important parts of the R&D-work are carried out by university-based groups. The support of these university-based nuclear-physics groups, including their local infrastructure, is therefore absolutely essential for the success of the programmes at the present facilities and future large-scale projects.

The very positive role played in nuclear theory by the ECT* centre in Trento is recognised and acknowledged, especially its mission of strengthening unifying contacts between nuclear and hadron physics and the future support for this centre should be maintained and expanded. However, it is also recognised that in the last decade not enough attention has been put into maintaining the expertise and activity in theory at universities. The current situation requires vigorous and instant action to ensure that the physics goals presented in the LRP can be realised. Therefore, **NuPECC recommends that efforts should be undertaken to strengthen local theory groups in order to guarantee the theory development needed to address the challenging basic issues that exist or may arise from new experimental observations.**

Considering its cultural interest and numerous beneficial applications to society, NuPECC stresses the necessity of maintaining a high level of competence in nuclear science and to increase the understanding of the field among the general public; nuclear science, therefore, should be an essential element of undergraduate curricula. **NuPECC recommends that efforts to increase literacy in nuclear science among the general public should be intensified.**

Specific recommendations As is clear from the preceding sections, research in all fields encompassed by nuclear science, from the smallest scales to the largest ones, has made vigorous strides in the last decade. Many questions have been answered. However, the answers often raised new questions paving the way to new directions in research in our continuing quest for the understanding of our universe from the tiniest building blocks, the leptons and quarks and the mesons that carry the forces, to the largest structures in the cosmos. To address these questions new facilities have been proposed or are under construction.

NuPECC recommends as the highest priority for a new construction project the building of the international "Facility for Antiproton and Ion Research (FAIR)" at the GSI Laboratory in Darmstadt. This new international facility will provide new opportunities for research in the different subfields in nuclear science. The envisaged facility for producing high-intensity radioactive ion beams in In-Flight Fragmentation (IFF) is highly competitive, if not surpassing in certain respects similar facilities either planned or under construction in the U.S. or in Japan. With the experimental equipment available at low and high energy and at the New Experimental Storage Ring (NESR) with its internal targets and electron collider ring, the new facility will provide worldwide leadership in nuclear structure and nuclear astrophysics research. This is in particular true for research performed with short-lived exotic nuclei far from the valley of stability. The high-energy high-intensity stable heavy-ion beams will facilitate the exploration of compressed baryonic matter with new penetrating probes. The high quality cooled antiproton beams in the high-energy storage ring (HESR) in conjunction with the planned detector system PANDA will provide the opportunity to search for new hadron states predicted by QCD and explore the interactions of the charmed hadrons in the nuclear medium. In short, this facility is broadly supported since it will benefit almost all fields of nuclear science with new research opportunities.

The Isotope Separation On-Line (ISOL) technique to produce radioactive beams has clear complementary aspects to the IFF method. First-generation ISOL-based facilities have produced their first results and have convincingly been shown to work. The next-generation ISOL-based radioactive ion beam (RIB) facility, EURopean ISOL (EURISOL), aims at increasing, beyond 2013, the variety of radioactive beams and their intensities by orders of magnitude over the ones available at present for various scientific disciplines including nuclear physics, nuclear astrophysics and fundamental interactions. **After GSI, NuPECC recommends the highest priority for the construction of EURISOL.** The presently running project is aimed at completing a design study of the EURISOL facility.

Because of this time-line for EURISOL NuPECC supports projects, which have intermediate planning and will be realised on a shorter time-scale. These include the second-generation ISOL facilities: **SPIRAL2** (GANIL, Caen), **SPES** (LNL, Legnaro), Upgrade **REX-ISOLDE** (CERN, Geneva) and **MAFF** (München). These projects that are planned or under construction will allow one to bridge the gap between now and the operation of EURISOL. Furthermore, the technical developments required for these intermediate-scale projects such as high-power proton/deuteron (p/d) superconducting linear accelerators (SPIRAL2, SPES), heavy-ion superconducting post-accelerator (SPIRAL2), or high-power production targets are precisely the ones needed for EURISOL. In this European strategy towards EURISOL, considering the technical synergies between the SPIRAL2 and SPES projects, NuPECC is very satisfied that GANIL and LNL are closely coordinating their technical design and development efforts.

An advanced ISOL facility such as EURISOL will use a high-power (several MW) p/d accelerator. A large number of possible projects such as neutrino factory, antiproton facility, muon factory and neutron spallation source may benefit from the availability of such a p/d driver, and synergies with closely and less closely related fields of science are abundant. Considering the wide interest in such an accelerator **NuPECC recommends joining efforts with other interested communities to do the RTD and design work necessary to realise the high-power p/d driver in the near future.**

NuPECC recommends with high priority the installation at the underground laboratory of Gran Sasso of a compact, high-current 5-MV accelerator for light ions equipped with a high-efficiency 4π-array of Ge-detectors. Such a facility will enhance the worldwide uniqueness of the present facility at Gran Sasso and the potential to measure astrophysically important reactions down to relevant stellar energies.

NuPECC considers the physics with a high-luminosity multi-GeV lepton scattering facility very interesting and of high scientific potential. Such a facility will allow addressing questions regarding hadron structure and performing precision tests of various QCD predictions. Therefore, **NuPECC encourages the community to pursue this research within an international perspective, incorporating it in existing or planned large-scale facilities worldwide.**

In order to exploit present and future facilities fully and most efficiently, advanced instrumentation and detection equipment will be required to carry on the various programmes. The project AGATA, for a 4π-array of highly segmented Ge detectors for γ-ray detection and tracking, will benefit research programmes in the various subfields of Nuclear Science pursued at the various facilities in Europe. **NuPECC gives full support for the construction of AGATA and recommends that the R&D phase be pursued with vigour.**

3. European Network of Complementary Large-Scale Facilities

In this chapter, a presentation of the network of the complementary facilities, constituting the competitive large-scale facilities of Europe, is made. Most of these facilities are recognised as Research Infrastructures (RIs) by the European Union (EU) Commission and therefore have enjoyed strong support within the EU Framework Programmes. This support has been in the programmes of Transnational Access to RIs, Research and Technical Development projects and Networks. Several of the laboratories have also been recognised as Marie Curie Training Sites. In all of these facilities, the selection of submitted scientific proposals is based on reviews by programme advisory committees with international participation, entirely on the basis of scientific quality and originality.

It is worth noting, that all these facilities and many others are described in a NuPECC Handbook, which is updated once every several years, the last being in December 1998. In this Handbook, a short description of the facilities, the available instrumentation, the procedure how to apply for beam-time, and the main fields of research is given. Also, other useful information such as contact persons, their telephone numbers, (e-mail) addresses is given. Here, a description of these facilities as they are at present is given. GSI, GANIL, LNL and ISOLDE are presented first, because they have approved, or shortly to be approved, large new projects. All other facilities follow in alphabetical order of the city of location. Nuclear physics experimental set-ups operated at DESY and CERN are presented at the end of this chapter.

GSI, Darmstadt, Germany

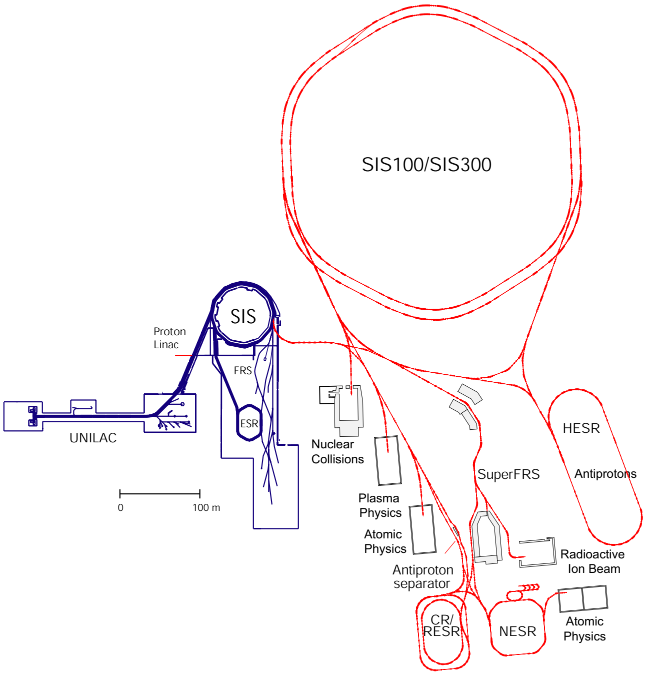
The Gesellschaft für Schwerionenforschung (GSI) Laboratory [http://www.gsi.de/] is located north of the city of Darmstadt in central Germany. Originally founded through an initiative from surrounding universities, it now serves a broad international community. GSI is operating a major accelerator facility with, in several aspects, world-wide unique characteristics.
The facility consists of three accelerators and associated experimental stations (Figure 3.1):

i) the original heavy-ion linac UNILAC, capable of accelerating ions ranging from protons to uranium to energies near 20 MeV/u;

ii) the booster synchrotron SIS18, built 15 years ago, which allows to boost ion energies up to 2 GeV/u for ions with mass-to-charge ratio of 2 (such as $^{16}O^{8+}$ and $^{36}Ar^{18+}$) and correspondingly somewhat lower energies for heavier nuclei;

iii) the ESR synchrotron ring, where the acronym stands for Experimental Storage Ring to emphasise its primary function is an experimental device for beam storage and internal-target experimentation.

Ion beams are produced in state-of-the-art ion sources and then accelerated. For the high-duty cycle ($\leq 40\%$) UNILAC intense beams of average currents up to several particle microamperes are obtained with an ECR source and a low-energy accelerating structure of the IH-type. The synchrotron with intrinsically very low-duty cycle for injection (typically 10^{-3}), high current, pulsed ion sources of the MEVVA and Penning types are used. Typical currents injected from the MEVVA source are 8 mA of Ar^{1+}, or 15 mA (charge current) of U^{4+}. The intensities for accelerated beams from SIS 18 are plotted in Figure 3.2. In addition to the beams of sta-



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- 2(4)x10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to a factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

Storage and Cooler Rings

- Radioactive beams
- e – A collider
- 10^{11} stored and cooled antiprotons (0.8 - 14.5 GeV)

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

Figure 3.1: Layout of the existing GSI facility (blue) with the UNILAC accelerator, the heavy-ion synchrotron SIS18, the fragment separator FRS and the experimental storage ring ESR; and the planned new facilities (red): the Super-conducting Synchrotrons SIS100/300, the accumulator ring RESR and Collector Ring CR, the New Experimental Storage Ring NESR, the Super Fragment Separator Super-FRS, the Proton Linac and the High-Energy Storage Ring HESR. Also shown are the target areas for plasma physics, nucleus-nucleus collisions, radioactive ion beams, and atomic physics experiments.

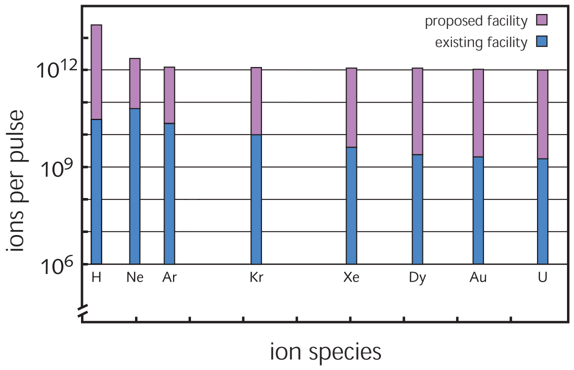


Figure 3.2: Beam intensity of various ion species with the present GSI accelerator and with the new facility.

ble nuclei, high-quality secondary beams at energies up to 1 GeV/u are produced by projectile fragmentation in a production target after beam is extracted from SIS18, and fragment selection in the GSI Fragment Separator (FRS). A diverse research programme, utilising the broad range of ion-species and beam energies available, exists at GSI. It involves sophisticated instrumentation and detector systems, including, as latest additions, the large-acceptance, high-resolution di-lepton spectrometer HADES for study of, for example, vector mesons in nuclear matter, and the Petawatt laser PHELIX for plasma physics and high electromagnetic field studies. More detailed descriptions can be found on the GSI Website. Research highlights from the last decade include, for example: the discovery of the heaviest elements, from Z=107 to 112; precision cooling of ion beams to relative momentum spreads below 10^{-6}; precision studies of QED in atomic physics of highly charged ions, such as the Lamb-shift in U^{91+} or the 1s g-factor in Pb^{81+}; studies of properties of nuclear matter around SIS energies through nucleus-nucleus collisions, including the "caloric curve" of the nuclear liquid-to-gas phase transition in multifragmentation, and the mass-shift of kaons in dense nuclear matter from subthreshold production; the shift of the pion-nucleus coupling constant in nuclear matter from precision spectroscopy of pionic atoms in heavy nuclei; accurate measurements of a range ($\sim$ 300) of unknown masses of unstable nuclei (most recently of neutron-rich nuclei approaching the r-process region) using the ESR in the electron-cooler or time-of-flight mode; and last but not least a range of studies in ion-matter interactions, ranging from materials science research using ion-track formation, to plasma physics with measurements of stopping power and atomic spectra of ions in high-density matter, to biological research and heavy-ion cancer therapy.

The International Future Facility for Antiproton and Ion Research (FAIR)

The present facility at GSI laboratory has unique research potential for the near and mid-term future. However, major advances will be needed to provide the beam intensities and characteristics necessary for the research programmes envisaged for the long-term future. Therefore, GSI together with its users and the international science communities has developed the concept for a future facility with intense and high-quality beams of ions and antiprotons. Here, a brief overview of the facility planned at Darmstadt is given. More detailed information is contained in the Conceptual Design Report (CDR) [1].

The research to be performed with this future facility covers, in the broadest sense, studies with energetic primary and secondary beams of ions of highest intensity and quality, including an “antimatter beam” of antiprotons. Technical challenges that arise from the requirements of highest beam intensity include new rapidly cycling superconducting magnets, both of the iron-core and of the cosine-theta types, and stringent vacuum requirements. High beam quality will be achieved in collector and storage rings with beam cooling, in particular high-energy electron-beam cooling of ion and antiproton beams. The proposed layout of the technical facility with the parameters of primary and secondary beams is shown in Figure 3.1.

The concept and layout of the new facility has evolved from the science requirements as follows: substantially higher intensities are achieved, compared to the present system, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the space-charge limit. The reduced charge state, and still a desired energy of up to 1.5-2 GeV/u for radioactive beam production, requires a larger magnetic bending power. These aspects are fulfilled by the SIS100 synchrotron. It also generates intense beams of energetic protons, up to 30 GeV, and from these antiprotons.

Heavy-ion beams of high energy, i.e. 25-30 GeV/u, are generated using ions in a high charge state plus the additional, somewhat slower but still rapidly cycling SIS300 (6T) synchrotron ring. The intensity required for these beams allows for long spills. Similarly, the SIS300 (6T) can be used as a stretcher for radioactive beams. Both, primary and secondary beams can be injected, cooled and stored in a system of rings with internal targets and in-ring experimentation. Rings may be shared for usage with different beams. Based on the developments and excellent experiences with cooled beams at the present GSI facility, the future programme will broadly take advantage of this aspect of beam handling. More details about the beam characteristics can be found in the CDR.
The facility allows research in five independent areas:

I. The investigations with beams of short-lived radioactive nuclei are expected to be performed in three experimental areas: In the Low-Energy Cave, where radioactive beams will be decelerated for, e.g., nuclear spectroscopy experiments.

   In the High-Energy Cave the reaction products of RIB collision at about 1.5-2 GeV/u with other nuclei can be studied. Third, a system of rings (Collector Ring (CR), New Experimental Storage Ring (NESR) and the electron ring (e-A Collider) for collisions with unstable nuclei) will allow a range of novel studies with stored and cooled beams (Figure 3.3).

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[1] [http://www.gsi.de/GSI-Future/cdr/]

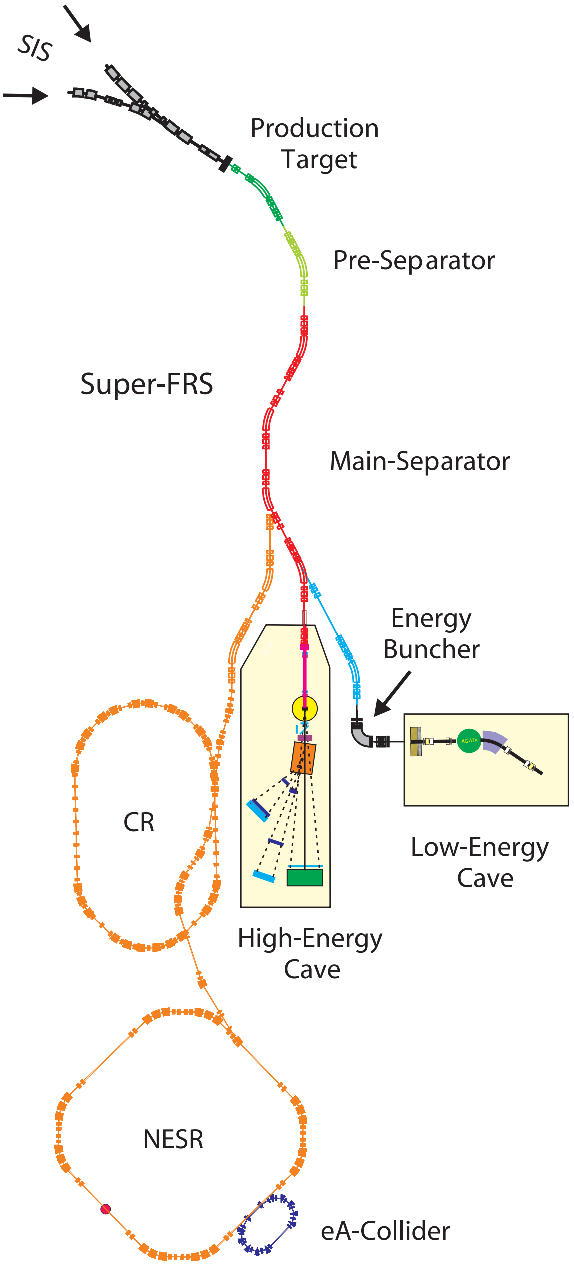

Figure 3.3: Layout of the Super-FRS, the storage rings, New Experimental Storage Ring (NESR) and Collector Ring (CR) and the experimental facilities for physics with rare isotopes.

II. Hadron structure and QCD is investigated at the High Energy Storage Ring (HESR). Up to 10^{11} Antiprotons with energies of 0.8-14.5 GeV can be stored in the HESR and studied with an internal proton target with the PANDA detector (Figure 3.4). For these experiments the cooling of the antiproton beam by electron cooling is essential.

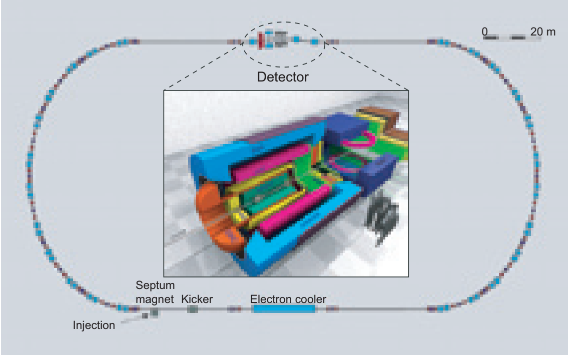

Figure 3.4: Layout of the HESR and the PANDA experiment.

III. The study of compressed, dense hadronic matter by nucleus-nucleus collisions at beam energies of 20-35 GeV/u allows to investigate the modification of hadron masses in nuclear matter at 5-10 times normal nuclear-matter density. This objective and the study of the transition to the quark gluon plasma at high baryon density is the task of the Compressed Baryonic Matter experiment CBM.

IV. The study of bulk matter in the high-density plasma state, a state of matter of interest for inertial confinement fusion and astrophysical settings by using the heating of matter with a combination of laser and ion beams.

V. The studies of Quantum Electrodynamics (QED), of extremely strong (electromagnetic) fields, and of ion-matter interactions are also part of the research programme at the new facility

An important consideration in the design of the facility was a high degree of truly parallel operation of the different research programmes. With the proposed scheme of accelerator and storage rings, maximum integrated beam time, or integrated luminosity can be provided for each of the different research programmes operated in parallel more or less like a dedicated facility. This high degree of synergy in facility performance will also lead to an increased scientific synergy between the different areas of research and to interdisciplinary intersections.

GANIL, Caen, France

The Grand Accélérateur National d'Ions Lourds (GANIL) [http://www.ganil.fr/] has been running since 1983 as a facility for fundamental research to investigate and consolidate knowledge about the atomic nucleus. The laboratory is operated jointly by the National Institute of Nuclear and Particle Physics (IN2P3/CNRS) and Direction des Sciences de la Matiére (DSM/CEA).

Nuclear physics research at GANIL is focused on the study of nuclei far from the line of stability and on dynamical and statistical aspects of nucleus-nucleus collisions.

The quality of beams delivered by the accelerators makes GANIL an outstanding centre for research used also by other disciplines, via laboratories associated with CIRIL (Centre Interdisciplinaire de Recherche Ions - Lasers, [http://www.ganil.fr/ciril/] and ISMRA, gathered in an interdisciplinary research hub. With GANIL and its industrial applications department, several specialised companies have been formed in areas ranging from the production of microporous membranes (filters) to the development of new electronic modules and ion sources.

The accelerator complex of GANIL comprises Electron Cyclotron Resonance (ECR) ion sources and five cyclotrons: two injectors and two separated-sector cyclotrons put in a cascade delivering stable beams and CIME large acceptance cyclotron for the acceleration of Radioactive Ion Beams (RIB). The following beams are currently available:

- High-energy heavy-ion beams from carbon (up to 95 MeV/u) to uranium (up to 24 MeV/u),
- RIB produced "in-flight" in SISSI device and ALPHA or LISE spectrometers in the energy range from $\sim$ 20 to $\sim$ 80 MeV/u,
- Accelerated RIB at very low (tens of keV) and medium energies (from $\sim$ 3 MeV/u to $\sim$ 25 MeV/u) from the SPIRAL facility,
- Medium-energy heavy-ion beams up to 13 MeV/u for C, or 4 MeV/u for U,
- Heavy-ion beams from an injector cyclotron, up to 1 MeV/u for C, or 0.4 MeV/u for U (IRRSUD facility),
- Light- and heavy-ion beams from ECR sources, up to $\sim$ 25 keV/unit charge (LIMBE facility).

Stable beam intensities in the 10^{11}-10^{13} pps range can currently be produced in either the medium- or high-energy lines.

GANIL offers a wide variety of top-level instruments dedicated to nuclear physics and interdisciplinary research. Among them are: VAMOS, SPEG and LISE magnetic spectrometers, and EXOGAM, INDRA and ORION the 4π γ-ray, charged-particle and neutron detectors, respectively. GANIL is an international outside-users facility. The user community is strong with 40% of its 700 members coming from outside of France. Of its 233 employees only 24 are nuclear physicists, which underlines its character as a host institution.

The SPIRAL2 Project The SPIRAL2 project at GANIL [2] is based on a multi-beam driver in order to allow both ISOL and low-energy in-flight techniques to produce RIB. A superconducting linac with an acceleration potential of about 40 MV capable of accelerating 5 mA deuterons and 1 mA heavy ions up to 14.5 MeV/u is used to bombard both thick and thin targets (Figure 3.5). These beams could be used for the production of intense RIB by several reaction mechanisms (fusion, fission, transfer, etc.) and technical methods (ISOL, IGISOL, recoil spectrometers,

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[2] [http://www.ganil.fr/research/developments/spiral2/]

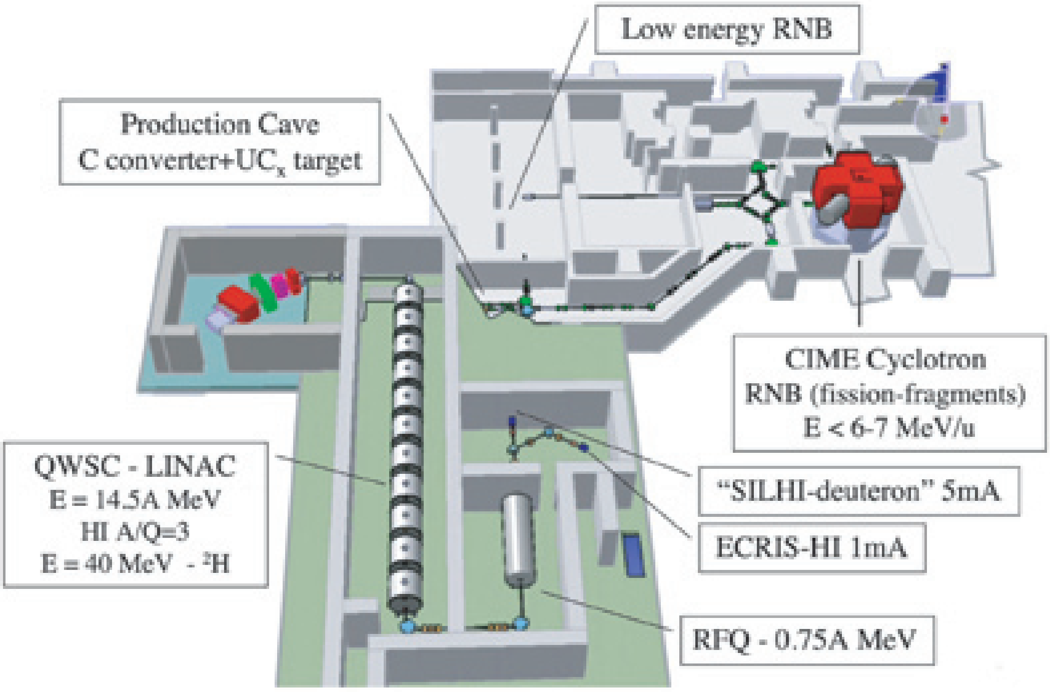

Figure 3.5: Layout of SPIRAL2.

etc.). The superconducting linac is optimised to A/q=3, better suited to light masses (A < 100) and adapted to the evolution of the ECR ion sources. This choice is also a compromise between the minimisation of the beam losses during acceleration (no stripping is used during acceleration) and the length of the machine. The accelerator will be constructed to allow for a future increase of the beam energy, preserving at the same time the very high beam intensity. The linac with a dedicated injector may serve as a first stage of a post-accelerator of the EURISOL facility.

The post acceleration of RIB in the SPIRAL2 project is assured by the existing CIME cyclotron, which is well adapted for separation and acceleration of ions in the energy range from about 3 to 10 MeV/u for masses A $\sim$ 100-150. SPIRAL2 beams, both before and after acceleration, can be used in the present experimental area of GANIL.

The production of ISOL-type RIB is based on fission of uranium target induced by neutrons, obtained from a deuteron beam impinging on a graphite converter ($> 10^{13}$ f/s) or by direct irradiation with a deuteron, ^{3}He or ^{4}He beam. The fusion-evaporation and transfer reactions involving heavy ions of up to 14.5 MeV/u might be used to produce mostly neutron-deficient nuclei. The above techniques will expand the range of RIB available at GANIL to heavier ones, both on the neutron-rich and neutron-deficient sides of the chart of nuclei (Figure 3.6). Several domains of research in nuclear physics at the limits of stability will be covered by this project, including the study of the r- and rp-process nuclei, shell closure in the vicinity of N=82 and N, Z=50 as well as the investigation of very heavy elements.

The very high-intensity stable and radioactive heavy-ion beams will also be available for interdisciplinary research, in particular thanks to the existing infrastructure (CIRIL and CYCERON laboratories). An important flux of about 14 MeV neutrons produced by SPIRAL2 might find important applications in material science (for example in the framework of the ITER project). The overall investment cost of the SPIRAL2 facility is estimated to be 40 MEuroand the first beam might be expected in 2008. From the point of view of performances, employed technical solutions and the proposed time schedule SPIRAL2 should be considered as an important intermediate step between the existing RIB facilities and EURISOL.

LNL, Legnaro, Italy

The Laboratori Nazionali di Legnaro (LNL) [http://www.lnl.infn.it/] is a European Research Infrastructure dedicated to nuclear and interdisciplinary research. The present research facilities consist of the Tandem-ALPI Accelerator Complex, hosting a 16 MV XTU-Tandem accelerator and a superconducting linac post-accelerator, of a 7.0 MV CN Van de Graaff (VdG) accelerator, mainly dedicated to interdisciplinary and biomedical research and of a 2.5 MV AN2000 VdG accelerator with a 2.5 MeV proton microbeam.

Nuclear physics research at LNL is mainly devoted to the study of nuclear structure and collisions at energies close to the Coulomb barrier. The experimental programme is conducted in collaboration with more than 100 institutions worldwide. The Tandem-ALPI complex provides typically more than 5000 hours per year of ion beams for measurements using different instrumentation like spectrometers or gamma detector arrays. An extensive experimental programme was and is presently carried out with the gamma-detector array GASP which addresses nuclear-structure problems at the forefront, such as those of isospin symmetry and mixing, superdeformations and exotic excitations. This year the array of Clover Ge detectors of the EUROBALL collaboration will be installed around the new PRISMA spectrometer and an experimental programme presently planned is aiming at extending our knowledge of the nuclear structure both for proton-rich and moderately neutron-rich nuclei. Quasi-elastic or multi-nucleon transfer reactions will be used to populate moderately neutron-rich nuclei along shell closures where nuclear-structure calculations predict radical changes in the shell structure. The expertise that will be gained in connection with this campaign is certainly very valuable and necessary for the future programmes with radioactive beams.

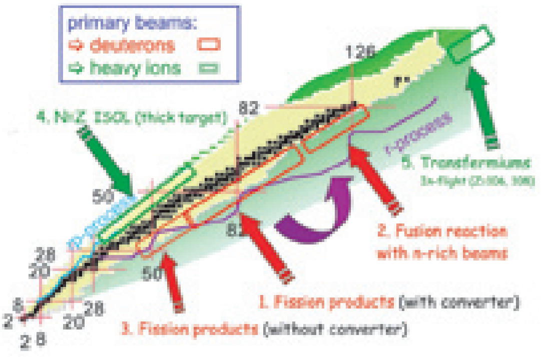

Figure 3.6: Chart of nuclei showing the expanded range of RIB available.

Figure 3.7: Areal view of Legnaro.

The activity related to the study of heavy-ion reaction dynamics is made with the 4π detector arrays for charged particles and heavy ions (8πLP) and GARFIELD. Experiments are dedicated mainly to understand the problem of thermalisation, the fission times, the gamma-width linked to giant dipole resonance properties and problems of interest also far from stability particularly for nuclear astrophysics.

Beside the activity at the experimental facility the laboratory is strongly involved in R&D programmes for the design and construction of future arrays for gammas and charged particles. It is important to mention in this connection AGATA for gamma-ray tracking together with the R&D on pulse shaping and segmentation for charged-particle detection. The MOT-trap dedicated to parity non-conservation experiments with francium isotopes produced via fusion-evaporation reactions is also now in operation and expected to provide important data on fundamental physical questions. Such activity will certainly benefit by the availability of a new high-intensity accelerator.

Based on the previous experience with superconducting machines, LNL is presently working on a design study of a high power proton and deuteron driver (SPES) to provide a second generation RIB facility.

The SPES Project The SPES (Study and Production of Exotic nuclear Species) project [3] at LNL aims at the construction of an intermediate size radioactive ion beam facility as a part of the European laboratory for radioactive ion beams EURISOL. SPES is expected to offer research opportunities for Nuclear Physics and interdisciplinary fields using radioactive ion beams covering the wide time gap until the completion of EURISOL, expected beyond 2013. now. This facility, having an intermediate size between the present generation and EURISOL, will allow both to develop an extensive physics programme and to boost the technological efforts (accelerator, production targets, detectors..) needed for EURISOL.

Moreover, the design work for SPES is perfectly integrated within the design and R&D work for EURISOL where SPES represents a part of the driver accelerator as well as an example for future high-intensity linacs (TRASCO [http://trasco.lnl.infn.it/]). A first design report of SPES was published in 1999 (LNL-INFN 145/99) while a detailed Technical Design Report (LNL-INFN 181/02) has been recently published.

Since the main aim of SPES is the production of a large variety of neutron-rich isotopes, which are not accessible using fusion-evaporation reactions, the project uses nuclear fission induced by high-energy neutrons for synthesising unstable elements. The fission target consists of ^{238}U, in uranium-carbide form. The neutrons are produced by a primary proton beam impinging on a thick ^{9}Be target. The main advantage of the two-targets method is that the beam power ($\sim$ 100 kW) is dissipated (mainly through electromagnetic interactions) in the first target (converter), while the second target (production target) only withstands the fission power (less than a kW). With a fission rate up to 10^{14} f/s a wide spectrum of unstable nuclei can be produced, with, for example, about 10^{11} ^{132}Sn per second produced in target. Once ionised these nuclei will be accelerated up to 15 MeV/u in the superconducting linac ALPI with an expected intensity of about 10^{8} ions/s at the experiments.

The proton energy of 100 MeV chosen for the driver allows to exceed 10^{13} f/s for a 4 Kg UC$_x$ target and a heat dissipation of 100 kW in the converter; this last value corresponds roughly to the limit for a solid target (non-liquid metals). The construction of a Be converter, conveniently cooled, is presently the object of a vigorous R&D programme. An interesting alternative, also under study at LNL, is the use of a ^{13}C target, which is expected to stand better the heat avoiding the toxicity of Be. First results with ^{13}C graphite are very encouraging (LNL-INFN 180/02).

The driver linac design based on independently-phased superconducting cavity linac (ISCL) and with a capability of 5 mA, is the same as for the corresponding part of the EURISOL project. The value of the beam current has been chosen according to the linac design, since a power level below 10 kW per amplifier can be achieved with solid-state technology. Moreover, an RF system of this kind is modular allowing an upgrade to 3 mA corresponding to one basic RF unit per cavity.

The main linac components are the off-resonance RF source TRIPS, the TRASCO RFQ and the ISCL. The source and the RFQ have been developed within the TRASCO research programme, aimed at the development

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[3] [http://www.lnl.infn.it/~spes/]

of a high-intensity linac for nuclear-waste transmutation. The source TRIPS is being commissioned at LNS, while the RFQ is under construction at LNL. The source and the RFQ, installed at LNL, will represent a unique facility, able to deliver 30 mA 5 MeV beams.

The following ISCL is the natural extension of the superconducting heavy-ion linac technology. The scheme of the project will resemble the one of the existing accelerator complex at LNL, using many independent resonators working in continuous-wave (CW) mode, but realised at higher frequency and with a much higher beam current. As a consequence new RF amplifiers (keeping the reliability of solid-state RF sources) and new cavities (with large beam hole and good field quality) are being developed. The re-entrant cavity, half-wave resonator and ladder cavity can be used. All cavities are built using Nb sheets that are electron-beam welded. The re-entrant-cavity prototype has already been built and tested up to its design field.

Such proton driver linac, thanks to the use of many independent superconducting cavities, can be seen as an "open accelerator" and, with an upgraded version of the front-end, it can accelerate ions with A/q up to three with a good efficiency ($\sim$ 100 MeV/q). This allows the use of different reactions, like fusion-evaporation or multi-nucleon transfer for producing unstable nuclei. The extended capabilities of the linac would also allow the acceleration of deuterons with an increased production of neutrons per beam Watt of about a factor 2 integrated over the whole solid angle, and up to 8 in the forward direction. In this way the rate of 10^{14} f/s can be exceeded.

Apart from the Nuclear Physics applications, an interdisciplinary use of the SPES facility is also the Boron Neutron Capture Therapy (BNCT). A 5 MeV, 30 mA proton beam produced by the first sector of the accelerator, the RFQ, using a (p,n) reaction on ^{9}Be and a heavy-water moderator, generates a flux of thermal neutrons of about 2.5×10^9 n/(s cm^2)) suitable for patient treatment. Here, a concentration of B in the neoplastic tissues will be achieved pharmacologically, so that the α and ^{7}Li particles emitted following n capture can achieve a very localised damage of these tissues. At LNL, the BNCT facility is foreseen to explore the cure of extended skin melanoma with this method.

A second n-production target for condensed-matter study can be added as a local facility for neutron scattering experiments. Such a facility can play an important role as a national neutron site being complementary to the use of a European spallation source (ESS).

Moreover, the installation of the high-intensity RFQ (TRASCO RFQ) makes possible the reliability and availability tests required by the ADS (accelerator-driven system) community in view of future nuclear-waste transmutation plants. The 30 mA, 5 MeV beam will also be available for the tests of new high-intensity linac structures.

In the proposed layout the facility is connected with the existing LNL complex. The main new construction is the driver-linac and RIB production building, west of Tandem-ALPI complex. Integrated in the same building there will be a part dedicated to BNCT.

The three experimental halls presently used at LNL will all be reached by accelerated RIBs. Additional experimental space will be available for low-energy experiments in the region of the mass selection. The upgrading of ALPI, and the installation of the new injector to RIBs, is possible in the existing vault with an upgrade of the cryogenic system and of some infrastructures. In the proposal the acceleration of ^{132}Sn up to 15 MeV/u is considered, corresponding to the installation of cryostats equipped with high-performance cavities in all ALPI locations.

The SPES facility is conceived with the possibility to be upgraded up to EURISOL specifications. An upgrading of the postaccelerator is also possible with an intervention in the layout of the complex. Two linac sections, 20 m each, for a final energy of 40 MeV/u (^{132}Sn), can be installed in the ALPI vault and in the third experimental hall. As alternative a 100 MeV/u linac, still injected by ALPI, could be installed in a separate tunnel to be built south of the ALPI vault.

The SPES facility at LNL is also very well suited for being used with the present instrumentation allowing nuclear physics research for systems very far from stability.

ISOLDE, CERN, Geneva, Switzerland

The ISOLDE facility at CERN [http://isolde.web.cern.ch/ISOLDE/] uses the 1.4 GeV proton beam from the CERN PS-Booster to produce radioactive ion beams (RIB) from fission, fragmentation and spallation reactions induced in thick targets using the ISOL technique. The experimental programme is conducted by a collaboration that contains members from about 80 institutions worldwide. ISOLDE provides typically 3000 hours per year of radioactive ions for measurements in 35-40 active experiments that make use of 5-10 independent spectrometers and other complex instruments in a typical year. The low-energy radioactive beams of exotic nuclei available at ISOLDE, presently unrivalled for many nuclear species in intensity, purity and beam quality, are crucial vehicles to understand the details of the nuclear many-body system at the extremes as well as increasing our knowledge about nuclear astrophysics and fundamental interactions and being an important tool for research in condensed-matter and life sciences.

Within nuclear-structure physics, broad research activities at ISOLDE map the nuclear system at extreme isospin through studies of ground-state properties and nuclear decay. Through the advent of post-accelerated beams with the REX-ISOLDE charge breeder and linear accelerator, probing nuclear properties using transfer reactions and Coulomb excitation of exotic nuclear species is now possible. REX-ISOLDE currently provides beams of energy 3.1 MeV/u into the super-efficient, highly segmented gamma-ray MINIBALL array at the secondary target position. REX is operational and has already accelerated several species of radioactive ions, e.g. 10,000 ions/s of ^{29}Na; it has the capability to accelerate mass-140 ions and heavier with efficiency of a few percent of the ion-source yield. In 2003 REX-ISOLDE was integrated into the standard operation of CERN facilities.

The experiments carried out at ISOLDE are diverse and state-of-the-art. In addition to a large range of detectors of different types for decay and in-beam experiment (such as the total absorption spectrometer TAgS and an advanced silicon array Si-BALL), there are instruments for laser spectroscopy (COLLAPS) and nuclear orientation of exotic nuclei, permitting studies of nuclear ground-state properties far from stability. The triple-trap ISOLTRAP spectrometer can routinely achieve accuracies of 10^{-8} in mass measurements of unstable nuclei, and is complemented by the MISTRAL spectrometer that is able to measure masses of the most short-lived species. The WITCH retardation spectrometer is an exceptional tool for weak interaction studies through nuclear beta decay. There is also advanced instrumentation for studies of surface science and solid-state physics.

HIE-ISOLDE Scheduled energy and intensity up-grades will increase the physics potential of ISOLDE even further [4]. The goal for the period up to 2008 will be to accelerate ions up to 5 MeV/u or higher, with an increase of primary beam intensity to 10 μA. This enhancement of the ISOLDE facility, shown schematically in Figure 3.8, is called “High Intensity and Energy ISOLDE” or HIE-ISOLDE. The energy upgrade can be considered in two phases: (1) to increase the energy to 4.1 MeV/u by 2005 that enables the Coulomb barrier to be reached for mass 150 symmetric reactions and (2) further increases in energy for applications using the widest variety of nuclear reactions. The ISOLDE hall will be extended in order to house the additional linac cavity resonators and other instrumentation such as new recoil spectrometers for detection of fusion products. Another new facility, REX*, will accelerate radioactive ions from a charge breeder source mounted on a 500 kV platform. This will provide low-energy beams with continuously variable energy from < 100 keV to > 10 MeV for astrophysics and

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[4] [http://isolde.web.cern.ch/isolde/hie-isolde.pdf]

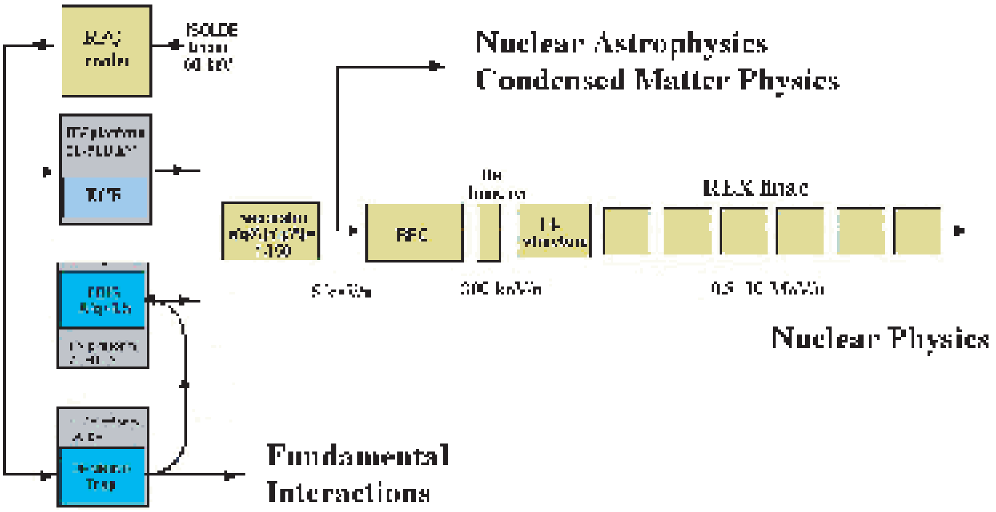

Figure 3.8: Scheme of HIE-ISOLDE.

condensed-matter studies.

In parallel with the energy upgrade, the proton beam intensity on the primary target will be increased. In the next few years, the available beam from the PS-Booster, through the provision of H^- injected beam from a new primary linac injector and a faster cycling time in the Booster itself, will be increased three-fold, resulting in a significant increase in beam available to ISOLDE. The development of primary target and ion-sources that can withstand the higher beam intensities will be pursued in parallel with the intensity upgrade.

The SPL project CERN is currently considering the scientific case for a high power proton driver, the Superconducting Proton Linac. This accelerator will provide 2.2 GeV, 11 mA pulsed (50 Hz) proton beams for enhanced injection to the PS and thence to the LHC, and to provide intense proton beams for other research programmes such as neutrino production (e.g. the beta-beam) and to a next-generation RIB facility. For the last application, the high repetition rate will give a lower peak intensity of the proton beam than the present PS-Booster ISOLDE facility (thereby increasing the target lifetime), while the average current for direct RIB production can be increased to 100 μA. The higher proton energy will give an order of magnitude increase (over that from the existing ISOLDE facility) in the formation cross sections for the light neutron-rich target fragmentation products, while operating the SPL at lower energies than the nominal 2.2 GeV permits the RIB production cross section of the spallation products to be optimised. The high power available also allows the use of a spallation target for production of neutron-induced intense beams of fission fragments in a secondary target.

The driver beam will be transported to both the existing ISOLDE facility and a new target area that is located underground. Post-accelerated RIB beams of energies up to and beyond 10 MeV/u will be transported to at least three experimental areas, with possibilities to be explored of injection into storage rings with electrons, muons, or antiprotons.

LNS, Catania, Italy

The Laboratori Nazionali del Sud (LNS) [http://www.lns.infn.it/] is mainly devoted to the study of nuclear collisions at intermediate and low energies, the latter also in view of the completion of the radioactive beam facility EXCYT. LNS features two accelerators: an electrostatic HVEC MP Tandem, maximum terminal voltage of 16 MV, and a K=800 superconducting Cyclotron currently accelerating heavy and light ions to 10-70 MeV/u.

In order to fulfil its scientific goals, LNS mainly relies on its accelerators and several related equipment. The most relevant detection systems developed and installed at LNS are listed below.
CHIMERA, a 4π multi-detector featuring about 1200 telescopes for charged particles, is currently being used for a detailed investigation of multi-fragmentation and is capable of measuring charge and mass of the heavy fragments produced in the reactions.
OUVERTURE, a multiple detection system composed of:
MEDEA, an $\approx \pi$ multi-detector featuring 180 BaF_2 scintillators for gamma and light-particle detection;
MULTICS, a forward array of 64 position-sensitive telescopes for fragment detection;
SOLE+MACISTE, a very forward spectrometer for mass and charge spectrometry of heavy ions; and
MAGNEX, a large acceptance (solid angle is 51 msr and momentum acceptance ±10%) magnetic spectrometer devoted to experiments with radioactive beams, is currently being installed.

Moreover, specific laboratories are dedicated to cutting-edge developments of accelerators, beam diagnostics, ion sources, detectors, nuclear targets and other challenging technological issues. In particular SERSE, today the most performing ECR ion source in the world, has been developed at LNS.

At the same time LNS pursues several multidisciplinary goals, with and without the use of particle beams. As an example, it is worth to mention CATANA, the only hadron-therapy facility in Italy, and the LANDIS laboratory for non-destructive archaeological analysis with nuclear techniques.

Figure 3.9: The CHIMERA multidetector array.

LNF, Frascati, Italy

The Frascati National Laboratories (LNF) [http://www.lnf.infn.it/], founded in 1955, are the oldest and biggest labs of INFN, the Italian agency devoted to fundamental research in nuclear and subnuclear physics. They were built to host the electron Synchrotron, which at that time, with its energy of 1.1 GeV, represented a world record. Around 1960, a new idea of accelerator was first conceived and demonstrated in Frascati: a colliding-beams accelerator. All modern elementary-particle storage rings descend from that first prototype, ADA (Anello di Accumulazione).

Subsequently, a large electron-positron collider (ADONE) was designed, built and brought to operation in 1969. ADONE, with its c.m. energy of 3 GeV, held for a while the world record in energy and its experiments paved the road to the understanding of particle physics. One of its main achievements was the observation of the abundant production of multi-hadron events, which later led to the discovery of a new degree of freedom of the quarks: the *colour*.

The presence of a very active community nurtured also the establishment of an important activity in nuclear physics, using the extracted beams from the LINAC and/or Compton backscattering as well as the first synchrotron light lines. Original ideas, like the jet-target or the tagged backscattered photon beam, are still in use worldwide.

After the phasing out of ADONE in the 90's, the same infrastructure was used to host DAΦNE, a high luminosity machine at 1 GeV c.m. energy (Φ-factory), aimed to a broad physics programme, ranging from CP and T violation studies, to physics of hypernuclei and to exotic atom properties.

With its high specifications, DAΦNE is also providing intense synchrotron radiation beams, especially in the infrared region (I.R.), where the extreme source intensity generates a large interdisciplinary interest coming from Life Sciences.

Presently DAΦNE holds by more than an order of magnitude the world record in luminosity at its design energy, and its performance is still improving. It provides colliding beams to 3 experiments, KLOE, FINUDA and DEAR and synchrotron light to 3 experimental lines (IR, UV, and soft X-Ray). It also delivers extracted beams from the LINAC (Test Beam Facility).

Among the new developments under study at LNF, a proposal to build a new ultra-brilliant and coherent X-ray source (Free Electron Laser) has been submitted to the Research Ministry and it has already been granted resources for R&D.

KVI, Groningen, The Netherlands

The Kernfysisch Versneller Instituut (KVI) [http://www.kvi.nl/] is a Dutch national institute which is funded by the University of Groningen and by the Dutch National Physics Foundation FOM. The main research activity at the KVI is experimental and theoretical nuclear physics, but there are important research activities in atomic physics and in applied nuclear physics.

Figure 3.10: A photo of the K=600 MeV, superconducting AGOR cyclotron at KVI.

The superconducting cyclotron AGOR (K=600) is capable of accelerating (vector-polarised) protons and (vector- and tensor-polarised) deuterons up to 190 and 180 MeV, respectively. Alpha particles and all other ions with q/A = 1/2, where q is the charge of the ion with mass A, can be accelerated to 90 MeV/u. Heavier nuclei can be accelerated up to an energy of 600 q^2/A^2 MeV/u.

There are two major experimental equipments for nuclear research at the KVI: the Big-Bite magnetic Spectrometer (BBS) and the Plastic Ball. A third detection system named BINA (Big Instrument for Nuclear-polarisation Analysis), which is an upgrade of the earlier SALAD (Small-Angle Large-Acceptance Detector), is under construction and is planned to be operational in 2004. All three equipments can be used in conjunction with ancillary equipment like the multi-detector systems EDEN (for neutrons), Forward Wall (for light charged particles), Silicon Ball, BBS polarimeter, TAPS, two Clover detectors and a large-volume ($\phi = 25$ cm, length = 35 cm) NaI detector. A special beam line has been set up with which radiobiology experiments pertinent to proton therapy can be performed. Another beam line is available for irradiation experiments.

Furthermore, a new facility called TRIμP [http://www.kvi.nl/~trimp/trimp.html], meant for trapping radioactive ions produced with AGOR, is under construction. It comprises a magnetic recoil separator, an RFQ and magneto-optical traps. The aim of the facility is to study physics beyond the Standard Model, but it will also allow studies in atomic and molecular physics. The complete set-up will be ready in 2005, but parts (e.g. the recoil separator) will be available already earlier.

In the Nuclear Geophysics Division (NGD), the applied-nuclear-physics group of KVI, BGO detectors are used to measure low radioactivity concentrations in soil cores (PHAROS core logger) and surveys of underwater bottoms and land and road surfaces (MEDUSA and PANDORA detectors). For more detailed analysis a counting laboratory with three low background HPGe gamma spectrometers is available. Furthermore, several set-ups are present for analysing radon exhalation and concentration.

COSY, FZJ, Jülich, Germany

Figure 3.11: Photo of the COSY ring.

The Institut für Kernphysik (IKP) at the Forschungszentrum Jülich (FZJ) [http://www.fz-juelich.de/ikp/] operates the COoler SYnchrotron (COSY) facility. It is predominantly dedicated to fundamental research in hadronic and nuclear physics. A major priority is the investigation of the properties and interactions of hadrons in the strongly non-perturbative regime of QCD. The main experimental approach is the measurement of the production of light mesons and hadrons with strange quark content. A further priority is the study of proton-nucleus interactions in the GeV range which is of interest for spallation sources and radiation protection.

The injection cyclotron provides beams of protons and deuterons with momentum of about 300 MeV/c - in the case of unpolarised beams with currents up to 10 μA and in the polarised case of roughly 1 μA. These beams can be used either directly for irradiation studies, or be transferred to COSY for further acceleration. COSY consists of a 184 meter circumference synchrotron that employs both stochastic and electron phase-space cooling in order to provide high quality proton and deuteron beams with a beam momentum of up to 3.65 GeV/c. During and after the acceleration phase the circulating beam can interact with targets placed in the ring. With up to 5×10^{10} ions in the accelerator ring, such internal experiments can be performed with typical luminosities of 10^{31} /(cm^2 s). Furthermore, the beam can be extracted from COSY, in either a single 200 ns pulse or evenly distributed over several seconds to minutes by using stochastic feeding, and then directed to one of the external target stations.

Several major apparatus are available for the internal experiments: The EDDA detector allows sensitive measurements of polarisation observables in proton-proton elastic scattering in which both the beam and target are polarised. The dipole spectrometers COSY-11 and ANKE both have high acceptance and resolution for meson-production reactions near the production threshold and include sophisticated kaon identification at ANKE. In addition, the PISA detector measures proton-induced spallation cross sections for a wide variety of nuclear targets.

The major external experiments include a large acceptance Time-of-Flight (TOF) spectrometer, which is ideally suited to measure the decay products of short lived particles such as hyperons. High-precision measurements of forward going ejectiles are performed with the double focusing Big Karl magnetic spectrometer. Moreover, target materials and the design for high power spallation sources are investigated at the JESSICA target area.

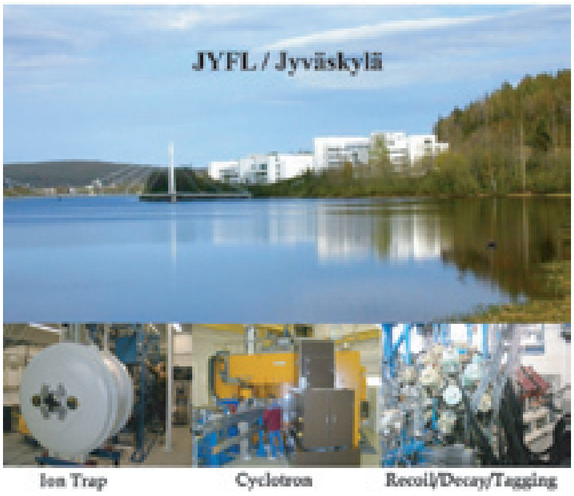

Figure 3.12: Jyväskylä accelerator laboratory.

JYFL, Jyväskylä, Finland

The Accelerator Laboratory of the University of Jyväskylä (JYFL) [http://www.phys.jyu.fi/] is a Finnish national facility with an international programme in education and research on atomic nuclei under extreme conditions as well as in related applications. As a university laboratory, the JYFL laboratory provides excellent conditions for graduate students and young scientists for active participation in experiments as well as in the design and construction of instrumentation. The nuclear physics and condensed-matter physics programme of the Department of Physics was awarded the status of Centre of Excellence in Finland for the period of 2000 - 2005.

The JYFL cyclotron (AVF, K=130) with its ion sources delivers one of the largest variety of light and heavy-ion beams in Europe providing more than 6500 beam hours per year. There are unique instruments available for experiments carried out at the JYFL accelerator:
The Ion Guide Isotope Separator On-Line (IGISOL) technique developed in Jyväskylä is an important new technology towards the next generation radioactive ion beam facilities. JYFLTRAP consisting of a Radiofrequency Quadrupole (RFQ) beam-cooler device and a high-precision Penning trap as well as a high-sensitivity laser spectroscopy set-up are combined with IGISOL. The gas-filled magnetic recoil separator RITU combined with European Ge-detector arrays and the focal-plane spectrometer GREAT from the UK as well as with the SACRED electron spectrometer form one of the leading installations in the world for studies of neutron-deficient heavy and superheavy nuclei in so-called Recoil Decay Tagging (RDT) experiments. The High Efficiency Neutron Detector System (HENDES) and a large universal scattering chamber are used for nuclear reaction studies. A special irradiation facility (RADEF) is used for ion-beam related material science research and testing of electronics components.

CRC, Louvain-la-Neuve, Belgium

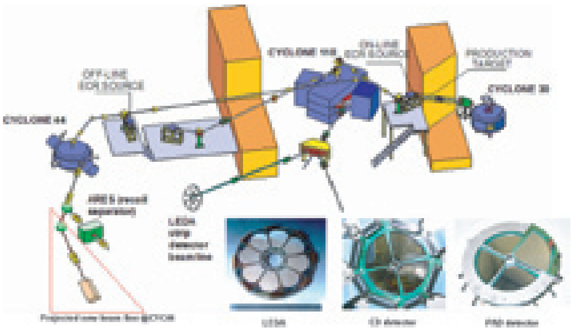

Figure 3.13: Schematic view of CRC Louvain-la-Neuve.

The Centre de Recherches du Cyclotron (CRC) [http://www.cyc.ucl.ac.be/], a European Large-Scale Facility since 1996, operates three cyclotrons: CYCLONE110, CYCLONE30 and CYCLONE44, for use by national and foreign experimental groups. Its unique character, in Europe and in the world, resides in the production of very intense and isobarically pure post-accelerated Radioactive Ion Beams (RIB) in the low-energy region (0.2 to 10 MeV/u), most suitable for studies in the fields of nuclear astrophysics and spectroscopy of light exotic nuclei. Beams of ^{6}He, ^{7}Be, ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{18}Ne, ^{19}Ne, ^{35}Ar are routinely produced and new RIB beams are under development. Other available beams include light and heavy ions (from gaseous and metallic elements) up to 4 MeV/u for Xe, and fast neutron beams, either mono-energetic in the 20 to 80 MeV range or continuous in the 6 to 70 MeV range, the latter being appropriate for dosimetry and radiobiology experiments requiring high LET.

Experimental facilities include a LEvel Mixing Spectrometer (LEMS), LEDA-type solid state detector arrays, the 4π neutron detector DEMON, the isotope separator on-line LISOL, the Astrophysics REcoil Separator (ARES), a very high-intensity neutron, a light-ion and a heavy-ion irradiation facility for radiation-effects studies. Powerful, open and versatile data-acquisition systems coupled to an integrated computer network and well-equipped mechanical and electronic workshops are available.

MAX-lab, Lund, Sweden

MAX-lab [http://www.maxlab.lu.se/] is a Swedish national laboratory which supports three distinct research areas: accelerator physics, research based on the use of synchrotron radiation and nuclear physics using energetic electrons.

Nuclear-physics research at MAX-lab has until recently been based on the access to an almost continuous 95 MeV electron beam, which has been used to produce mono-energetic (tagged) photons in the energy range 10 to 75 MeV. Presently, the nuclear-physics activity is closed down because of an ongoing upgrade, which will result in a 250 MeV stretched electron beam for nuclear-physics research. The new beam is expected to be available in spring 2004.

The expected parameters of the upgraded nuclear-physics beam line are: Maximum energy 250 MeV; duty factor 50-80 %; operating current ≤ 40 nA; beam emittance 0.25 mm·mrad. Tagged photons between 18 and 225 MeV will be available with an energy resolution of between 150 and 800 keV depending on the desired photon energy range. There are also plans to set up a coherent bremsstrahlung source for linearly polarised photons.

The main instrumentation for Nuclear Physics experiments are:
Tagging spectrometers for electron detection, 4 large NaI photon detectors ($\phi = 25$ cm, length = 25 cm), 2 large liquid-scintillator neutron detectors (0.36 m^2 each), 16 small liquid-scintillator neutron detectors ($A_{tot} \approx 0.35$ m^2), telescopes of Si-Si or SSD-HPGe for charged-particle detection, targets of L^4He and LH_2 and 10 plastic-scintillator time-of-flight detectors ($10 \times 20 \times 300$ cm^3)

MAMI, Mainz, Germany

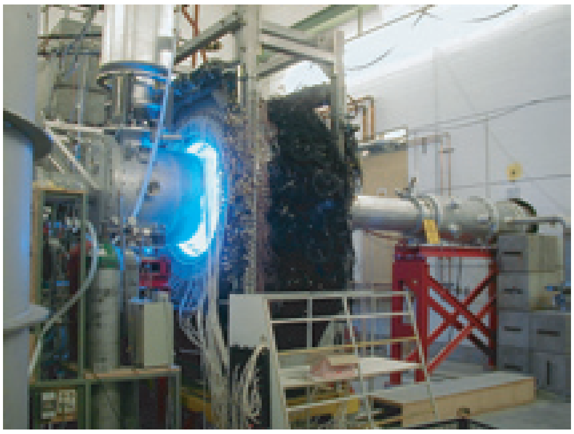

Figure 3.14: The PbF_2-calorimeter of the A4 collaboration at the MAMI facility in Mainz.

The Mainz Microtron (MAMI) facility [http://www.kph.uni-mainz.de/] consists of an injection linac and three consecutive racetrack microtrons accelerating electrons in steps of 15 MeV up to 855 MeV. The beam of MAMI excels with a very small diameter (< 0.1 mm), a tiny halo ($< 10^{-5}$ of the intensity is outside a diameter of 1 mm), and a very good energy definition ($\Delta E/E \approx 10^{-6}$). The most important quality, however, is the effectively direct current beam. With this beam several coincident particles at high-beam current can be detected and, therefore, the measurement of small coincidence cross sections is possible. The high intensity of unpolarised and polarised beams of electrons and photons allows the investigation of significant and well-defined observables of hadrons and nuclei.

The energy of the MAMI accelerator is being upgraded to 1500 MeV by the addition of a double-sided harmonic microtron (MAMI C). This microtron will provide the same beam quality as MAMI B and allow for a considerable extension of the mass range and for the study of open strangeness.

The scientific work in MAMI is organised in collaborations developing and exploiting some major experimental installations:

- A1 Collaboration: Electron Scattering. The A1 Collaboration uses a set-up of three magnetic spectrometers turning around a common pivot for coincidence experiments with protons, pions, and electrons. A focal-plane polarimeter in one of the magnetic spectrometers for protons and further calorimetric detectors for neutrons are also available. To take full advantage of MAMI C the high-momentum magnetic spectrometer, KAOS from GSI, will be integrated into the set-up in the A1 hall.

- A2 Collaboration: Real Photons. The A2 Collaboration is centred around a photon tagger providing unpolarised, linearly polarised, and circularly polarised photons with a flux of up to 10^8 photons per second. It uses a polarised proton/deuterium target together with a variety of other detectors. The most important ones are the DAPHNE detector from Saclay, a non-magnetic detector with 2π geometry, and the SLAC Crystal Ball.

- A4 Collaboration: Parity-Violating Electron Scattering. This collaboration measures the weak form factors of the nucleon. It uses a set-up of fast PbF_2 crystals together with very fast integrated read-out electronics and a high-power liquid hydrogen/deuterium target.

- X1 Collaboration: Coherent X rays. The X1 Collaboration investigates several mechanisms producing coherent X rays as parametric X-ray radiation, Smith-Purcell effect, transition radiation, and undulator radiation. One typical example of the results is the phase sensitive imaging of biological objects.

Figure 3.15: Villa Tambosi at ECT*.

ECT*, Trento, Italy

The European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*) [http://www.ect.it/] offers a unique combination of projects in high-level scientific exchange, dedicated research and advanced training to the international community of scientists working in Nuclear Physics (Nuclear Structure, QCD and Hadron Physics, Matter under Extreme Conditions) and related fields (Particle Physics, Astrophysics, Condensed-Matter Physics, Quantum Physics of Small Systems).

ECT* is the only Centre of its kind in Europe. Each year typically more than 600 visitors from more than 35 different countries contribute to the scientific activities of the Centre. ECT*, an institutional member of NuPECC, is European in concept and operates in a context of European Universities and Laboratories. The scientific projects of ECT* are carried out under the responsibility of its international Board of Directors.

The goals of the Centre are:

- To coordinate and perform in-depth research on topical problems at the forefront of contemporary developments in Theoretical Nuclear Physics;

- To strengthen the interchange between theoretical and experimental studies;

- To foster interdisciplinary contacts between Nuclear Physics and its neighbouring fields;
- To encourage talented young physicists by arranging for them to participate in ECT* projects.

The ECT* projects and training programmes are primarily directed towards the basic understanding of the atomic nucleus and its fundamental constituents. In addition, they promote active scientific exchange spanning the wide spectrum of cross-disciplinary applications that emerge through the concepts, methods and techniques developed and used in nuclear-physics research, from quantum information theory via Bose-Einstein condensation to tumour therapy with ion-beams. The ECT* computing facilities include a powerful cluster and an APEmille, which can be used for a broad range of applications requiring large-scale computations.

TSL, Uppsala, Sweden

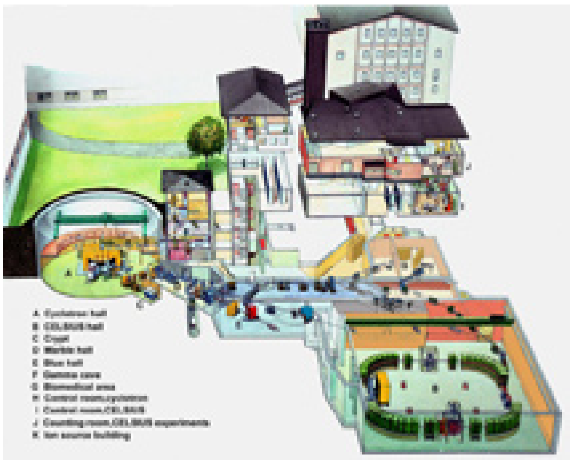

Figure 3.16: The The Svedberg Laboratory at Uppsala.

The The Svedberg Laboratory (TSL) [http://www.tsl.uu.se/] is a Swedish national facility for accelerator-based research operating two accelerators, the Gustaf Werner cyclotron and the CELSIUS cooler and storage ring. About half of the beam time is devoted to basic research in nuclear and low-energy particle physics mainly at the CELSIUS ring, whereas the other half goes to interdisciplinary research in application-oriented projects for accelerator-driven systems, radiation damage, dosimetry, materials physics, biomedicine and proton therapy.

The cyclotron acts as the injector to the CELSIUS ring, but can also be run separately giving a wide range of ion beams of various energies up to 185 MeV for protons and 8 MeV/u for xenon ions. The cyclotron has an internal ion source for light ions as well as an external ECR ion source for multiply charged heavy ions. One of the beam lines contains a mono-energetic neutron source for energies between 25 and 180 MeV where intensities of 10^6 neutrons per second can be obtained. Several of the application-oriented projects mentioned above profit from the neutron beam as well as from different ion beams in a separate beam line. The materials-physics community at TSL is using heavy-ion beams for a wide range of material modification research projects. Beam lines with irradiation facilities are also available for biomedical research and radionuclide production. The proton-therapy projects at TSL include regular narrow-beam treatments and commissioning work on a magnetic scanning head for broad-beam irradiations of large tumours.

The CELSIUS ring is a synchrotron, equipped with an electron cooler, giving maximum energies of 1.36 GeV for protons and 470 MeV/u for light ions ($A \leq 20$) with a charge-to-mass ratio of 1/2. The main activity at the CELSIUS ring is the study of light-meson production and decay. Pions and eta mesons are produced in light-ion collisions and the reaction and decay products are recorded in the CELSIUS/WASA 4π detector located in one of the straight sections of the CELSIUS ring. Another important activity at the CELSIUS ring is the study of multi-fragmentation processes in heavy-ion collisions. The collision products are detected in the internal CHICSi 3π charged-particle multi-detector array.

DESY, Hamburg, Germany

The Deutsches Elektronen-Synchrotron (DESY) [http://www.desy.de/] is one of the research centres in the Helmholtz Association, with locations in Hamburg and Zeuthen near Berlin. DESY's main task is to operate large accelerator facilities, which are used for scientific research into elementary-particle and nuclear physics as well as research using synchrotron and Free Electron Laser radiation. DESY is a nationally funded research centre open for scientists of all nations.

Elementary-particle and nuclear physics research is currently conducted at DESY Hamburg at the HERA (Hadron-Electron Ring Accelerator) electron/positron-proton storage ring. HERA accelerates protons to 920 GeV and electrons or positrons to 27.5 GeV. Presently four large experiments collect data at the HERA ring.

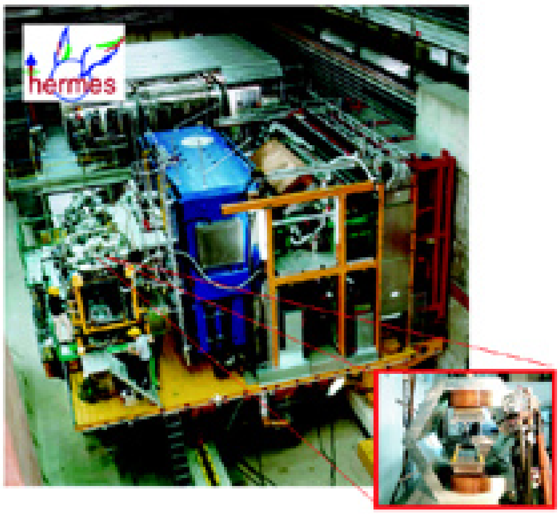

Figure 3.17: Photograph of the HERMES spectrometer at DESY. The lepton beam passes the experiment from left to right. The transverse target magnet is shown as an insert on the right.

Nuclear physics questions are addressed by the HERMES [http://www-hermes.desy.de/] experiment, investigating the quark-gluon and spin structure of nucleons. Longitudinally polarised electrons or positrons are scattered off spin-polarised gas targets. HERMES is a magnetic spectrometer instrumented with tracking detectors, ring-imaging Cherenkov counters, transition-radiation detectors, calorimeters and muon detectors (see Figure 3.17). The experiment will be significantly upgraded in 2004 with a new component (silicon detector combined with a scintillating fibre tracker and a photon detector) to measure recoil protons. This will enhance the capabilities to reconstruct exclusive reactions and the experimental resolutions, giving access to measurements related to the concept of Generalised Parton Distributions. The international HERMES collaboration consists of about 180 scientists from 32 institutes out of 11 countries. HERMES plans to take data until 2007.

CERN, Geneva, Switzerland

CERN, the European Organisation for Nuclear Research [http://www.cern.ch/] located in Geneva on both Swiss and French territory, is the world largest particle and nuclear physics laboratory dedicated to fundamental research. CERN's accelerator-based research programme, which ranges from atomic and nuclear physics at the low energy end to the discovery and study of fundamental particles at the highest energies, includes a broad and active research in ultra-relativistic heavy-ion collisions. Starting in 1986 with light ions (Oxygen and Sulphur) at 200 GeV/u and since 1994 operating with Lead, several generations of fixed target experiments at the Super Proton Synchrotron (SPS) have studied the physics of dense and hot strongly interacting matter.

Currently CERN is constructing the Large Hadron Collider (LHC). In addition to operating with proton beams at 14 TeV, the LHC baseline programme includes both proton-nucleus and nucleus-nucleus collisions at a centre-of-mass energy of 5.5 TeV/u for Pb-Pb. The nuclear programme will be centred around the dedicated heavy-ion experiment ALICE and the COMPASS experiment.

ALICE (A Large Ion Collider Experiment) [http://alice.web.cern.ch/Alice/] is a general-purpose heavy-ion detector designed to study the physics of strongly interacting matter and the quark-gluon plasma in nucleus-nucleus col-

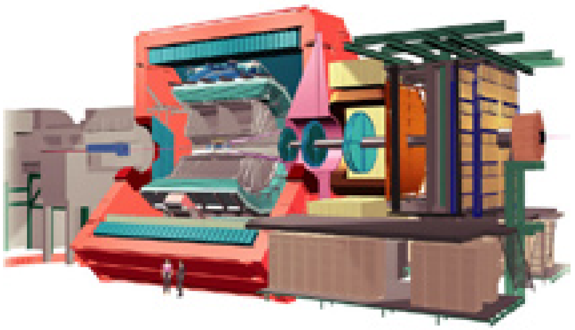

Figure 3.18: Schematic view of the ALICE detector.

lisions at the LHC. The detector is designed to cope with the highest particle multiplicities anticipated for Pb-Pb reactions (over 10000 charged particles per event in the central acceptance) and it will be operational at the start-up of the LHC. ALICE consists of a central part, which measures event-by-event hadrons, electrons and photons, and a forward spectrometer to measure muons. The central part, which covers polar angles from 45° to 135° over the full azimuth, is embedded in a very large solenoid magnet inherited from the L3 experiment at LEP. It consists of an inner tracking system of high-resolution silicon pixel, drift and strip tracking detectors; a cylindrical time-projection chamber; three particle identification arrays of time-of-flight, ring-imaging Cherenkov and transition-radiation detectors and a single-arm electromagnetic crystal calorimeter. The forward muon arm (2° to 9°) consists of a complex arrangement of absorbers, a large warm dipole magnet, and fourteen stations of tracking and triggering chambers. Several additional smaller detectors are located at forward angles. The ALICE collaboration currently includes about 1000 physicists and senior engineers - both from nuclear and high-energy physics - from close to 80 institutions in 28 countries.

Data taking is scheduled to start with proton beams in 2007, followed by Pb-Pb collisions at the end of the first year of LHC operation. In addition to heavy systems, ALICE will study collisions of lower-mass ions, which are a means of varying the energy density, and protons (both pp and p-nucleus), which not only provide reference data for the nucleus-nucleus programme but are of interest in their own in the study of strong-interaction physics (QCD).

The **COMPASS** (Common Muon Proton Apparatus for Structure and Spectroscopy) [http://wwwcompass.cern.ch/] experiment is set up at the CERN SPS North Area and uses the M2 secondary beam which delivers both high energy (polarised) muons and hadrons. It has a broad physics programme which aims at a deeper understanding of nucleon structure and confinement. The main physics observables, which are studied are: 1) the polarisation of the constituents of a polarised nucleon, using the polarised muon beam, and 2) the mass and decay patterns of light hadronic systems with either exotic quantum numbers or strong gluonic excitations and the leptonic decays of charmed hadrons, using hadron beams.

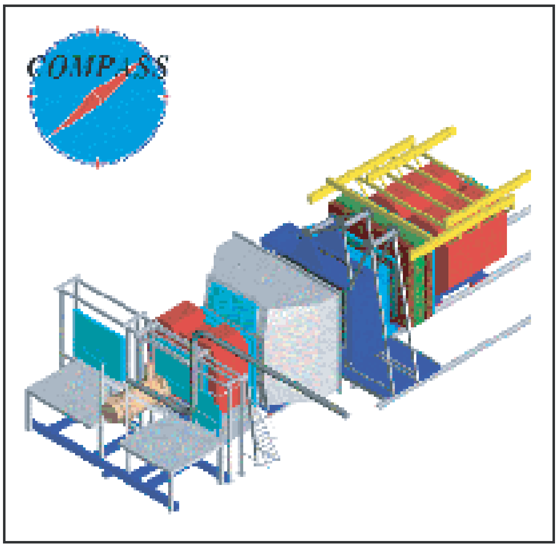

Figure 3.19: Schematic drawing of the COMPASS spectrometer at CERN. The muon beam passes the experiment from lower left to upper right.

The COMPASS apparatus combines very high rate beams with a modern two-stage fixed target magnetic spectrometer. The design of detectors, electronics and data-acquisition (DAQ) system allows to handle beam rates up to 10^8 muons/s and 5×10^7 hadrons/s with a maximal interaction rate of $\simeq 2 \times 10^6$/s. A variable target region allows for the use of a polarised target

(^6LiD and NH_3 are used as target material) in a new large acceptance superconducting magnet, a LH_2-target or a solid target combined with-high resolution silicon trackers. Particle tracking is performed using several stations of scintillating fibres, silicon detectors, Micromegas and gas chambers using the GEM-technique. Planar drift chambers, straw tubes and MWPC's are used as large-area tracking devices. Muons are identified in large-area Iarocci-like tubes and drift tubes downstream of muon absorbers. A large acceptance RICH is used for particle identification up to 50 GeV/c downstream of the first spectrometer magnet. The trigger is formed by several hodoscope systems and two hadron calorimeters. Electromagnetic calorimetry is being installed upstream of the hadronic calorimeters in each spectrometer section. The read-out mostly follows the pipeline principle and the DAQ handles up to 10^5 events/s which are sent into an on-line computing farm. About 2×10^4 events/spill are being recorded centrally, requiring a steady data stream of $\simeq$ 40 MB/s.

Until 2005, COMPASS focuses on the programme using high-energy muons. An upgrade (or completion) of the spectrometer is being prepared allowing to perform the full physics programme for the period from 2006 until 2010. Presently 12 countries, 23 Institutes and $\simeq$ 210 physicists participate in COMPASS.

4. Quantum Chromodynamics

Convenor: W. Weise (Italy and Germany);
F. Bradamante (Italy), J. Bijnens (Sweden), M. Birse (United Kingdom),
M. Garçon (France), M. Vanderhaeghen (Germany),
G. van der Steenhoven (The Netherlands), A. Zenoni (Italy),
NuPECC Liaison: T. Walcher (Germany)

4.1 Conceptual framework

Over the last decade the physics of hadrons and the physics of nuclei, once distinct fields explored by separate communities, have grown into a joint venture with a common root: Quantum Chromodynamics (QCD), the theory of the strong interaction. This theory emerged from the current algebras of the 1960's by way of the quark and parton models. By explaining the observed patterns in the spectrum of hadrons and the scaling behaviour seen in deep-inelastic scattering, these developments showed that quarks are the basic constituents of hadrons, and hence of nuclei.

Quarks are fermions with an intrinsic angular momentum (spin) of 1/2 and an electric charge whose magnitude is either 1/3 or 2/3 of the electron's charge. They also carry a property known as "colour" which can take three possible values and which controls the strong interactions between quarks. Six different types of quarks are known. Three of these are light, in the sense that their masses are much smaller than the nucleon mass. These include the "up" and "down" quarks (denoted u and d) which are the primary constituents of normal atomic nuclei. There is also the "strange" quark (s) which is somewhat heavier but which may make significant contributions, particularly in dense matter. Then there are three heavy quarks: "charm", "bottom" and "top" (c, b and t) which play much smaller roles at low energies.

QCD is a quantum field theory of quarks interacting with spin-one bosons known as gluons. Like all theories of fundamental interactions in particle physics it is a gauge theory: its form is unchanged under "rotations" of the three-valued colour charge. What makes QCD fundamentally different from Quantum Electrodynamics is the fact that the gluons carry colour charges and so interact amongst themselves, unlike photons which are neutral. It is this highly nonlinear dynamics of the gluon fields which lies behind key features of QCD such as confinement (the absence of free colour-charged objects in nature) and asymptotic freedom (the fact that quarks and gluons interact weakly at high momenta or short distances).

In any quantum field theory, virtual particles which result from quantum fluctuations lead to the strengths of interactions varying with momentum, or "running". In QCD this means that the coupling strength becomes small for particles with high momenta. On distance scales smaller than 0.1 Fermi, this asymptotic freedom permits us to treat QCD as a perturbative theory of point-like quarks and gluons.

In contrast, at distance scales of the order of 1 Fermi the running coupling becomes large, and a perturbative expansion in powers of this quantity is no longer valid. In this nonperturbative regime, which corresponds to the energies and momenta relevant to most of nuclear physics, the particles we observe are not quarks and gluons but colourless baryons and mesons. Both regimes, perturbative and nonperturbative, are explored experimentally either by studying the responses of hadronic systems to high-precision probes at various energy scales or by creating conditions of high density or temperature in high-energy heavy-ion collisions [1].

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[1] See also the chapter on Phases of Nuclear Matter.

Conceptually, low-energy QCD has many features in common with condensed-matter physics. The ground state or vacuum is a complex, strongly interacting system, filled with condensates of quark-antiquark pairs and gluons. The observed particles respect only a subset of the full symmetries of the theory. As in condensed-matter physics, we have two main theoretical tools to try to understand such systems: direct numerical simulation of the theory, and construction of effective theories for the low-energy degrees of freedom. The first approach, known as Lattice QCD, is starting to yield reliable results for the ground-state properties of hadrons and for the phase structure of QCD at finite temperature.

Despite the complexity of the QCD ground state, underlying symmetry principles and the patterns of symmetry breaking can provide important guidance for the second approach to the low-energy regime. In particular QCD with light quarks has an approximate chiral symmetry (which would be exact in the limit of massless quarks). This symmetry is spontaneously broken by the condensation of quarks and antiquarks in the vacuum. Pions are identified with the Goldstone bosons corresponding to this symmetry, which explains their small mass and the fact that they interact only weakly at low energies. This makes it possible to represent low-energy QCD by an effective field theory of pions and nucleons (and their strange partners), known as Chiral Perturbation Theory.

While we have controlled expansions of QCD in the two limiting situations, at very high energies as a perturbative theory of quarks and gluons, and at very low energies as a perturbative theory of pions, the true challenges lie between these extremes. Some of the most striking experimental facts which have their origins in the nonperturbative regime and which cannot yet be conclusively derived from QCD are the following:

- **Mass gap**
  There is a characteristic mass gap of about 1 GeV which separates the QCD ground state (or "vacuum") from almost all of its excitations, with the exception of the pion. How do these masses arise for hadrons which are built out of almost massless quarks and massless gluons?

- **Colour confinement**
  Quarks and gluons are not observed as free particles but are always trapped inside colourless hadrons. What are the mechanisms responsible for this phenomenon, and in particular what role do gluon fields play in it?

- **Spontaneous breaking of chiral symmetry**
  Pions are quite distinct from all other hadrons: they have very low masses and interact only weakly at low energies. Their properties can be well explained by treating these particles as the Goldstone bosons associated with spontaneously broken chiral symmetry. How are the condensates responsible for this generated? Under what conditions is this symmetry restored?

QCD is currently the best example we have of a nonperturbative quantum field theory, defined by a set of simple and fundamental rules but giving rise to an enormously rich range of physical phenomena. Moreover it is the only such theory that we are able to probe with high precision and under a wide variety of conditions. How its basic constituents (quarks and gluons) arrange themselves to form baryons and mesons, how these interact collectively in nuclear systems and how such systems behave under conditions of extreme temperature or density, these are key issues for nuclear physics.

With these key questions in mind, we highlight some of the experimental and theoretical challenges for the future. These will then be discussed in more detail in the rest of this chapter.

Substantial progress can be expected over the next decade in the following areas and topics:

- **The role of glue**
  The gluon field is the fundamentally new element of QCD that makes the dynamics of

strong interactions so much different from any other basic force in nature. Gluons play an important role in the intrinsic structure of the nucleon. In particular, being spin-1 bosons, the gluonic contribution to the total spin 1/2 of the nucleon has been a persistent puzzle. In the coming decade several experiments will provide new data on this key issue.

QCD predicts the existence of gluon-rich states known as glueballs. It also predicts hybrid states consisting of quark-antiquark pairs with excitations of the gluon field that holds the pairs together. The search for such states, the study of their decay modes and the investigation of their mixing with "conventional" states is one of the major experimental and theoretical challenges for the future.

- **Quark dynamics**
  The internal quark-gluon structure of hadrons is encoded in a well-defined hierarchy of correlation functions, the simplest of which are the parton distributions. In recent years, much progress has been made in developing a broader framework of so-called Generalised Parton Distributions (GPDs) which promise a clearer connection between fundamental QCD, phenomenology and experimental observables. Significant advances in this field are anticipated in the near future, especially because observables (such as single-spin asymmetries and exclusive cross sections) have been identified that can be used to extract information on parton correlations and quark orbital motion, for which no data exist so far.

  The spectroscopy of hadrons and the detailed investigation of their decays has been a traditional cornerstone in the understanding of the physics of strong interactions. Meson and baryon spectroscopy for systems with charm quarks is less well studied. Precision experiments which can explore these states will provide much novel information.

- **New theoretical developments**
  Increasingly accurate results are now emerging from large-scale simulations of QCD on four-dimensional Euclidean space-time lattices. Improved analytical methods for removing artifacts of discretisation, together with steadily increasing computer power, give rise to the expectation that decisive breakthroughs are at hand.

  "Integrating out" the colour degrees of freedom from QCD leads to an effective field theory of hadrons. The spontaneously broken chiral symmetry of QCD is the basis for a systematic expansion of this theory at low energies. The resulting Chiral Perturbation Theory is applied to mesonic systems as well as to a variety of processes involving mesons in interaction with a single nucleon. These studies are essential for analysing the response of the nucleon to low-momentum electromagnetic probes. The approach is being extended to describe nuclear forces and low-energy properties of light nuclei [2].

  While lattice QCD and effective field theory methods are promising theoretical tools, each within its own limits of applicability, much of the current experimental interest lies in regimes where no systematic expansion of QCD is known and for which lattice QCD is poorly suited. In these areas, as well as in the rapidly developing field of Generalised Parton Distributions, there is a useful role to be played by well-founded models, inspired by QCD but based on quasiparticles, such as consituent quarks, and collective degrees of freedom, such as Goldstone bosons and instantons. It will be important to develop these approaches further, and in particular to make closer contact with lattice QCD and systematic expansions.

- **Chiral symmetry**
  Dynamics based on the approximate chiral symmetry of QCD forms a guiding theme for the well-developed programmes exploring the low-energy frontier of strong interaction physics. These include high precision experiments on meson-meson and meson-nucleon scattering processes and, in particular, the use of electromagnetic probes to map out a

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[2] See also section 2 of the chapter on Nuclear Structure.

vast amount of detailed information about the pion cloud of the nucleon and the structure of the pion itself. Form factors, electromagnetic polarisabilities and meson production at threshold are crucial testing grounds for chiral perturbation theory. Applications of effective field theory methods to near-threshold reactions involving two nucleons will provide further systematic information. The challenges posed for the next decade are the further improvement of experimental precision and the selection of the most significant observables.

Insight into the physical mechanisms governing the mass gap in the hadron spectrum can be gained from studies of changes to this spectrum in nuclear systems, and from analyses of these changes in the context of the broken chiral symmetry of QCD. Experimental programmes which can shed light on this include high-energy heavy-ion collisions as well as high precision measurements of low-energy meson-nuclear states.

- **QCD and nuclear matter**
  Several distinct QCD-related phenomena occur in interactions of partons (high-momentum quarks and gluons) with a nuclear environment. One of them goes under the name of colour transparency. This refers to the formation of colour dipoles, such as quark-antiquark pairs, and their propagation through the medium. Another important issue is the energy loss that partons experience when passing through matter. A detailed description of the underlying physics of such processes is crucial in a broader context. Specifically it is needed for understanding the mechanisms involved in the ultra-relativistic heavy ion collisions which are being used to explore the QCD phase diagram. This field draws together parton physics and the study of hadronic matter under extreme conditions.

  A valuable source of information on non-conventional forms of baryonic matter is provided by systems with one or more strange or heavy quarks. Hypernuclei (nuclei containing strange quarks) have long been used for this and such studies should be pursued further, especially now that new facilities become available which feature an unprecedented energy resolution. Additional insights are forseen if nuclear systems with one or more charm quarks can be produced and studied at an appropriate facility.

4.2 Physics issues

4.2.1 New theoretical developments

Lattice QCD

The non-perturbative nature of QCD at large distances forms an obvious barrier for analytic treatments. However, important conceptual and technical progress has been made towards accurate simulations of the theory on a discrete lattice of space-time points. These demand both sophisticated numerical methods and raw computing power. Developments on both fronts mean that the quality of lattice computations is now beginning to reach the level at which meaningful comparisons with actual observables are feasible. Recent results include hadron masses and form factors, key properties of the nucleon (such as magnetic moments and the axial coupling constant relevant to neutron β-decay), as well as moments of structure functions.

These simulations use Monte-Carlo methods to perform a path integral over configurations of gluon fields. In the absence of quarks, the weighting of any configuration can be obtained from its action. In QCD, integration over the quark fields introduces the determinant of the quark Dirac operator into the weighting. Constructing this entails the high computational expense of inverting a huge matrix. This is often circumvented by an enormous simplification: the quenched approximation, in which this determinant is replaced by a constant. Doing this amounts to discarding most of the quantum fluctuations of the quark fields, in particular the multiple quark loops representing virtual quark-antiquark pairs, and it means that some contributions from such “sea” quarks are missing from physical observables.

While up to now most lattice calculations have relied on the quenched approximation, the steadily increasing power of large-scale computing facilities is starting to permit more extensive simulations of the full theory, including quark loops to all orders. Even so, current calculations are limited to relatively large quark masses, typically an order of magnitude larger than the actual masses of the u- and d-quarks. These correspond to pion masses of at least 0.5 GeV, which is too large to reliably predict chiral aspects of pion and nucleon dynamics in the real world.

Further significant improvements in lattice technology are expected in coming years. Although simulations with realistically small quark masses may still be out of reach for the foreseeable future, ultimately such efforts may not be necessary. Low-energy QCD in the light-quark sector is realised in the form of an effective field theory based on chiral symmetry. This theory can be used to extrapolate from lattice results obtained at higher u- and d-quark masses to the real world. Once lattice calculations are possible with pion masses of around 300 MeV, reliable extrapolations using these methods should be able to close the remaining gap between lattice QCD and actual observables. In combination with improvements in gluon and quark actions which permit the use of larger lattice spacings, as well as further increases in computing speed, this sets the scene for lattice QCD to make major contributions to the field as a whole.

Parton distributions

The asymptotic freedom of QCD means in effect that small-sized configurations of quarks and gluons can form useful probes of hadronic structure. Such configurations can be created in reactions such as deep-inelastic scattering (DIS), semi-inclusive DIS, Drell-Yan processes, or hard exclusive reactions. A crucial feature of all these processes is “factorization”: the fact that one can cleanly separate the hard (high-momentum) and soft (low-momentum) aspects of the interactions. The hard part of the scattering amplitude can be calculated using QCD perturbation theory whereas the soft parts of the amplitude, which describe how a given hadron reacts to some small-sized configuration, or how such a probe is transformed into hadrons, lie in the realm of non-perturbative QCD. These parts can be parametrized in terms of quark and gluon distributions, whose extraction requires close collaboration between experimentalists and theorists.

The unpolarized distributions describe the probability that a particular flavour of quark or a gluon carries a fraction x of the momentum of a fast-moving nucleon. QCD predicts how these distributions evolve with the hard resolution scale and this is now routinely calculated to next-to-leading order (NLO) in the strong coupling constant. Higher-order treatments are also under development. Analyses of DIS data have now mapped out the unpolarized quark and gluon distributions down to momentum fractions $x \sim 10^{-4}$ and over a wide range of scales. These results provide a benchmark for the steady progress being achieved in perturbative QCD.

For the helicity distributions, the present state-of-the-art is at next-to-leading order in the strong coupling constant. Analyses of polarized DIS have shown that less than a third of the spin of the nucleon is carried by the intrinsic spins of the quarks. The origin of the remainder of the nucleon’s spin is an important open question. In fact the NLO analysis of these experiments suggests that the gluons make an important contribution. However the present data cover only a limited range of resolution scale and so there is still a large uncertainty on the polarized gluon distribution extracted in this way. A more direct determination is possible using the photoproduction of heavy quarks, and in particular the production of pairs of charmed mesons. Recently, NLO analyses of this process have become available and these will allow us to pin down much more accurately the gluonic contribution to the spin of the nucleon.

The above mentioned distributions are incoherent single-parton densities in the nucleon. Information on coherent effects in the nucleon wave function can be obtained from hard scattering processes where a finite momentum is transferred to a nucleon. Examples include deeply virtual Compton scattering ($ep \to ep\gamma$) and exclusive electroproduction of light mesons. Qualitatively one can think of these as removing from the nucleon a quark of given flavour, momentum and spin, and replacing it in a controlled way by another quark, in general with a different flavor, momentum and spin (see Figure 4.1). Work in the last few years has shown that the amplitudes for such processes factorize into hard scattering parts and a set of generalized parton distributions (GPDs) which contain new information on the nonperturbative structure of the nucleon. In the forward limit these GPDs reduce to ordinary parton distributions but when a finite momentum fraction is transferred the GPDs become sensitive to coherent effects such as quark-quark momentum correlations or quark-antiquark configurations in the nucleon. Integrals of these distributions over the average momentum fraction carried by the quarks can provide information on properties of the nucleon that are not otherwise accessible. In particular, the second moment of a specific combination of GPDs gives a measure of the total angular momentum carried by quarks in the nucleon, information which would be complementary to that extracted from polarized DIS.

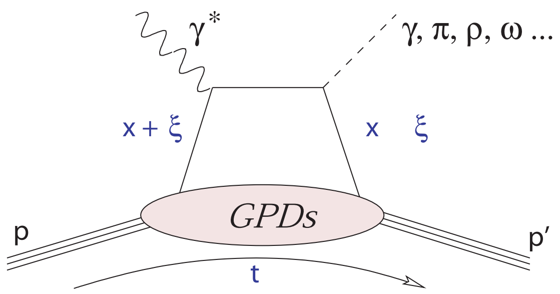

Figure 4.1: A hard electroproduction process on a proton, leading to a photon or a meson in the final state. Such reactions can be used to investigate Generalised Parton Distributions (GPDs).

Effective field theory

Effective field theory (EFT) has become a major tool for nuclear physics in recent years. Underpinning it is the observation that field theories do not have to be fundamental; all that is needed is a clear separation of scales between the physics of interest and the underlying physics. Nonrenormalizable field theories, which in principle depend on an infinite number of parameters, can then be very useful at a given level of finite "resolution".

To formulate such a field theory, one first finds the important degrees of freedom for the problem and writes down a Lagrangian containing all possible terms allowed by symmetries. Next one identifies a principle for systematically organising these terms in order of importance: a "power counting" which associates with each term some power of a small quantity. At a given order in these small quantities, only a limited number of terms are needed, whose strengths can be determined either from experiment or with other theoretical methods. The importance of this approach is its generality: if any further assumptions are introduced, they are clearly visible. These theories play an important role in three areas of nuclear physics: low-energy meson physics, single-nucleon processes near threshold, and the low-energy physics of two or more nucleons.

Spontaneous breaking of chiral symmetry requires the presence of a set of very light particles, known as Goldstone bosons. For QCD, these particles are the pions, which are separated from all other states by a mass gap of order 1 GeV. Goldstone's theorem requires that the interactions of these particles vanish at very low energies. Kaons and η mesons may also be treated in this way, albeit with caution because their masses are between three and four times larger than that of the pion.

The resulting EFT is then a low-energy expansion formulated in terms of the Goldstone bosons with a small parameter provided by the ratio of the energy or momentum to the mass gap. The systematic expansion in this small parameter, chiral perturbation theory, is now basis for much theoretical work in this area. In the meson sector the combination of EFT and dispersion relations is proving to be a very useful tool. Applications to pion-pion scattering are now theoretically fully under control.

In the baryon sector too, there is an energy gap between the nucleon and its excited states. The effective field theory here describes states with a single nucleon and any number of Goldstone bosons, and the power counting is in terms of the momentum divided by the mass gap. A significant technical complication, the presence of the large nucleon mass in all calculations has been solved by making a nonrelativistic reduction. Calculations now routinely include the first three orders in the expansion and have been applied with some success to processes such as meson-nucleon scattering, meson photoproduction, and Compton scattering (see Figure 4.2). Other areas under active investigation are the inclusion of the Δ resonance, and the treatment of relativistic effects, particularly in nucleon form factors.

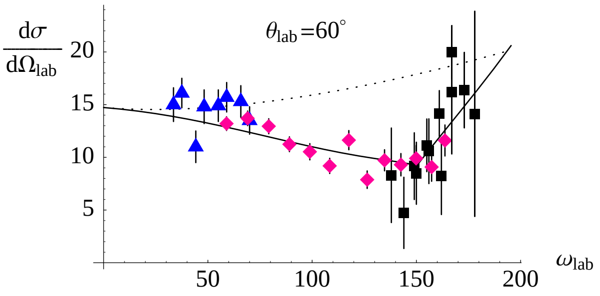

Figure 4.2: Prediction of fourth-order chiral perturbation theory (solid line) for Compton scattering cross section on the proton, compared with recent data from Mainz (diamonds) and older data from Illinois (triangles) and Saskatoon (squares). Also shown is the prediction of the Born and π^0 anomaly terms only (dotted line).

In recent years there has been major progress in extending these ideas to systems of two or more nucleons. The problem which had to be overcome here is that simple dimensional counting of energies over a mass gap leads to very large higher-order corrections. This is because there is a bound state just below threshold, the deuteron, in the $^3S_1$ channel and a resonant state just above threshold in the $^1S_0$ channel. Since perturbation theory cannot generate bound states, some terms in the interaction must be resummed to all orders, while still retaining a well-defined ordering principle. This was achieved using renormalisation group arguments to incorporate an additional low-energy scale in the counting, namely that of the large scattering lengths.

At very low energies, well below the pion threshold, the resulting EFT provides a systematic way to extend the effective-range expansion to describe electromagnetic and weak interactions of two-nucleon systems. Progress is now being made towards applying it to three-nucleon systems. At higher energies, pions should be included as explicit degrees of freedom. However the strong pion-nucleon coupling makes this problematic, at least in the s-wave channels. In more peripheral partial waves, the centrifugal barrier means that nucleon-nucleon interactions are weaker. Analyses of these channels now show good evidence for the two-pion exchange force predicted by the chiral expansion.

QCD-inspired models

At this point, it is important to stress the distinction between theory and models. A theory is a framework in which observables can be calculated directly from underlying principles, in the present case those derived from QCD. Its application generally involves various approximations but, at least in principle, these can be improved upon systematically. In addition a theory should be capable of specifying the limits of its validity. An approach which does not satisfy simultaneously *both* of these criteria is a model.

Perhaps the most important use for models is to identify the dominant physics involved in particular processes and hence to indicate what might be learned from future experiments. Successful model descriptions can provide bridges from areas where QCD can be applied directly to a broader range of phenomena where rigorous approaches are not at present available.

A first class of such models is based on quasiparticle and collective degrees of freedom. These can provide a reasonably good description of the hadron spectrum in terms of constituent quarks. The addition of a flux tube picture for the gluonic degrees of freedom makes it possible to reproduce most of the spectrum. While flux tubes have been shown to exist using lattice QCD (at least for infinitely heavy quarks), the emergence of constituent quarks remains mysterious. It is generally believed that their masses are associated with the spontaneous breaking of chiral symmetry. This is embodied in versions of constituent quark models which include couplings to pions and so satisfy constraints of chiral symmetry. Attempts to connect these models more closely to QCD invoke configurations of gluon fields such as instantons and colour monopoles.

Closely related to these are collective models, where baryons emerge as solitonic configurations of Goldstone boson fields (Skyrmions). Many of their predictions correspond to those of a quark model with a very large number of colours of quark. Recent versions of these models, where the mesons are generated as quark-antiquark pairs, naturally give rise to an antiquark "sea" and can be used to predict sea parton distributions. However connecting these models more closely to QCD remains an open problem.

The second class of models is based entirely on hadronic degrees of freedom. These are typically Lagrangians which satisfy some constraints of chiral symmetry and which are formulated in terms of physical mesons and baryons, including resonances. At present they provide one of the main tools for understanding the intermediate-energy domain. More systematic applications of chiral symmetry constraints and matching to QCD short-distance behaviour will lead to further progress in this area.

Finally, further improvement is also to be expected in the use of unitary resummations to extrapolate the results of chiral perturbation theory to higher energies. These approaches are able to describe several intriguing properties of the scalar meson sector as well as excited baryons.

4.2.2 Role of glue

Spin of the nucleon

In the naive quark model, the spin of the proton is carried by its three valence quarks (see Figure 4.3). However, in recent years we have learned that the gluons and possibly the orbital angular momentum of the quarks and gluons also contribute to the total spin content of the nucleon. This is commonly expressed by the following equation

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z, \tag{4.1}$$

where $\Delta\Sigma$ represents the summed contributions of the quarks spins, ΔG the contribution of the gluons, and L_z the orbital angular momentum of the partons.

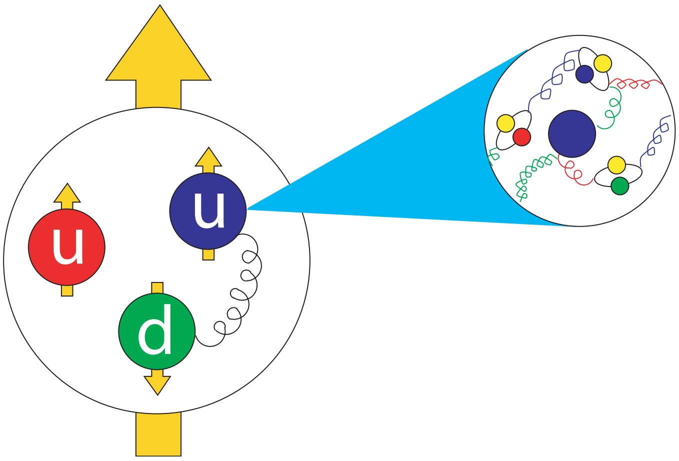

Figure 4.3: The (spin) structure of the nucleon. Apart from the contribution of the valence quarks, the gluons and sea-quarks may contribute as well (enlargement). Not shown in the figure is a possible orbital angular momentum contribution of the quarks and gluons.

Experimental information on the summed quark contributions has been obtained in polarized deep-inelastic scattering experiments. The results of such experiments are expressed as the longitudinal spin (or helicity) distribution function $g_1(x)$. When integrated over, this yields a value for $\Delta\Sigma$. Data on $g_1(x)$ have been obtained in various experiments carried out at CERN, DESY and SLAC. Their results are in good agreement with each other. On the basis of these data the total quark spin contribution $\frac{1}{2}\Delta\Sigma$ to the nucleon spin is found to be 0.1–0.3, indicating that additional carriers of angular momentum are needed in the nucleon.

To understand further the spin structure of the nucleon, the flavour dependence of the spin distribution functions has been determined. This is done in semi-inclusive deep-inelastic scattering experiments, in which one of the final hadrons is detected. The type of hadron (usually a π^+, π^-, K^+ or K^- meson) provides a tag on the flavour of the struck quark. The results of such measurements reveal that the polarization of the u-quarks is parallel to that of the proton, while the polarization of the d-quarks has the opposite orientation. Most importantly, the sea quarks have been found to carry very little polarization.

As the polarizations of the valence and sea quarks taken together cannot account for the full spin of the nucleon, efforts are now being made to measure the gluon polarization. Although QCD analyses of the polarized structure function $g_1(x)$ indicate that the gluon polarization could be large and positive, no direct measurements of ΔG exist. The proposals for determining ΔG are based on identifying photon-gluon fusion events in deep-inelastic scattering experiments. In these processes the virtual photon annihilates with a gluon from the target to produce a quark and its antiquark. The asymmetry of the process is sensitive to the gluon polarization.

HERMES has recently explored this process by detecting pairs of hadrons with high transverse momentum. This has yielded a positive value for ΔG but with large statistical and systematic uncertainties. The recently started COMPASS experiment at CERN will provide a much more precise measurement of the gluon polarization based on the identification of photon-gluon fusion events by detecting either charmed particles or high-p_T pairs of hadrons. This experiment has been designed to be able to map out the x dependence of ΔG. In the future, complementary data on the gluon polarization are expected to come from the RHIC-spin program at BNL using polarized proton beams.

Glueballs and hybrids

Simple constituent quark models have been remarkably successful in explaining most features of the observed meson spectrum. However, the QCD spectrum is much richer in content than that of the naive quark model. Gluons, which mediate the strong force between quarks, also carry colour charges and are able to interact with each other. The gluon-gluon interaction is the distinct feature of QCD held responsible for one of its spectacular consequences: confinement. It is also the source of another striking prediction of QCD: the existence of gluon-rich states known as glueballs, and of mixed states of quarks and gluonic excitations known as hybrids.

QCD-based "chemistry" suggests a variety of unconventional hadron configurations, such as meson-meson molecules bound by residual QCD forces, or more complicated color-neutral multiquark states such as $qq\bar{q}\bar{q}$ or $qqqq\bar{q}$. All these states should appear superimposed on the ordinary meson and baryon spectra.

The experimental observation of these exotic particles, in particular glueballs, would confirm one of the most important features of QCD. On the other hand, the non-existence of such states would pose a genuine problem for our understanding of hadronic physics in the context of QCD.

At present, the best candidate for the ground state glueball has emerged from antiproton-proton annihilation experiments performed at LEAR. This rather narrow state, the $f_0(1500)$, has the quantum numbers $J^{PC} = 0^{++}$. Its mass and width are consistent with predictions of lattice QCD for the ground state scalar glueball. However, the definitive identification of the $f_0(1500)$ as a glueball is complicated by its possible mixing with nearby conventional $q\bar{q}$ scalar mesons. The unambiguous identification of those $q\bar{q}$ states, including the scalar $s\bar{s}$, and the clarification of the multiquark ($qq\bar{q}\bar{q}$) content of the $a_0(980)$ and $f_0(980)$ mesons, are important steps that need to be further pursued. This last issue is being explored by the KLOE experiment at DAΦNE.

The mixing between predominantly gluonic bound states and neutral, flavour-singlet mesons means that some "conventional" meson states may contain significant glueball admixtures in their wave functions. Indeed, the possibility of a glueball component in the η' meson has been argued for many years. However, the recent measurement of the ratio $\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$, by the KLOE experiment at DAΦNE finds a value which limits the glueball content of the η' to at most 10–15%.

Candidates for hybrid states have been identified in $\pi^- p$ reactions at BNL and in $\bar{p}p$ annihilation at LEAR. A striking feature is that their production rate in $\bar{p}p$ annihilation is comparable to that of normal $q\bar{q}$ states. However, several predictions put the 1^{-+} hybrids at masses around 2 GeV/c^2. The discrepancy between these predictions and the experimentally measured states needs further clarification.

The COMPASS experiment at CERN can study Primakoff and diffractive production of light-quark hybrid mesons in the 1.4–3.0 GeV/c^2 mass region, including the candidates just mentioned. A 200 GeV pion beam will be used to measure pion-photon and pion-Pomeron reactions leading to selected hadronic final states. The relative strength for production of hybrids compared with other close-lying states is expected to be significantly larger than in previous experiments, leading to substantially reduced uncertainties.

Until now, the search for glueballs and hybrids has been mainly restricted to the mass range below 2.2 GeV/c^2. In the case of central production in proton-proton collision, another gluon-rich process, production of higher mass states is limited by the fall-off of the cross section with the inverse square of the mass of the state. Also, radiative J/Ψ decay, which could produce gluonic hadrons up to 3 GeV/c^2, lacks the required statistics. For a more complete understanding of the nature of gluonic excitations, a careful study of the spectrum of glueballs and hybrids up to 5 GeV/c^2 is an absolute necessity.

Central parts of the physics programme using the PANDA detector at the High-Energy Storage Ring (HESR) planned at GSI are the search for gluonic excitations in the charmonium sector and the continuing hunt for glueballs, including highly excited states with exotic quantum numbers. Light hybrids (with masses up to 2.5 GeV) will be a focus of the proposed 12 GeV upgrade of the Jefferson Lab facility.

Going to higher masses in the search for gluonic hadrons provides several advantages:

- Normal light-quark systems have a complicated spectrum. Nearly a hundred states with widths of ∼100–400 MeV are known in the mass interval 1–2 GeV/c^2. In the charmonium region only eight narrow states exist in the 0.8 GeV/c^2 interval below the $D\bar{D}$ threshold, and the continuum above is relatively smooth. This makes it likely that any exotic states in the 3-5 GeV/c^2 mass region can be resolved and identified unambiguously.
- Lattice QCD and various models all predict low-lying charmonium hybrids with masses between 3.9 and 4.5 GeV/c^2, the lowest state having the exotic quantum numbers $J^{PC} = 1^{-+}$. Three of the eight lowest-lying charmonium hybrids have spin-exotic quantum numbers, hence strong mixing effects with nearby $c\bar{c}$ states are excluded.
- Quantum number conservation and dynamical selection rules imply that charmonium hybrids below the $\bar{D}D^{**}$ threshold of 4.3 GeV/c^2 cannot decay into D mesons and so their widths should be small. Hybrids that can decay into $D\bar{D}$ are expected to have widths similar to the 25–40 MeV widths of the known vector states $\Psi(3S)$, $\Psi(4S)$ and $\Psi(5S)$.
- Nucleon-antinucleon annihilation can produce gluons as well as quark-antiquark pairs within a volume corresponding to the range of the strong interaction. As a result ordinary mesons and gluonic hadrons should have similar chances of being formed. Indeed, experiments at LEAR indicate that production rates of $q\bar{q}$ states are similar to those of states with exotic quantum numbers.
- In the mass range that is accessible to the HESR project, lattice QCD suggests the existence of about 15 glueball states, some with exotic quantum numbers. For example, the lightest glueball with the exotic quantum numbers 2^{+-} is predicted to have a mass of

> 4.3 GeV/c^2. For such glueballs the mixing with normal mesons should be suppressed. As a consequence they are predicted to be rather narrow and easy to identify experimentally.

Searches for glueballs and hybrids in this energy region can be performed in parallel with studies of charmonium spectroscopy at the proposed PANDA detector. In addition, by comparing different production mechanisms it should be possible to find unambiguous signatures of these exotic states.

4.2.3 Quark dynamics

Transversity

"Transversity" refers to a third structure function which describes a novel aspect of the dynamics of quarks in the nucleon. While the structure functions $f_1(x)$ and $g_1(x)$ represent the momentum and spin distributions of the quarks (see sections 4.2.1 and 4.2.2), the third function $h_1(x)$ represents the transverse spin distribution of quarks, that is the probability of finding a quark with its spin-orientation parallel to that of the nucleon when the nucleon spin is perpendicular to the incident beam (see Figure 4.4). Almost nothing is known at present about the transversity distribution $h_1(x)$, even though it is of great interest since data on it would enable us to investigate two remarkable QCD-based predictions.

Gluons are predicted not to contribute to the transverse spin distribution and so the structure functions $f_1(x)$ and $h_1(x)$ are expected to differ considerably. As a result both the dependence of $h_1(x)$ on Q^2 and the integral over $h_1(x)$ (known as the tensor charge, $\delta\Sigma_q$) should be quite different from their longitudinal counterparts. The well-known QCD scaling behaviour of $f_1(x)$ (which is largely driven by the gluon contributions) is predicted to be essentially absent for $h_1(x)$. In addition the tensor charge is predicted to be much larger than the integral over $g_1(x)$ which leads to $\Delta\Sigma$.

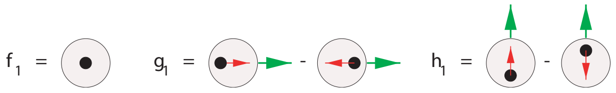

Figure 4.4: The different spin orientations of the three functions $f_1(x)$, $g_1(x)$ and $h_1(x)$ that give a full account of the momentum, helicity and transverse spin structure of the nucleon.

Inclusive deep-inelastic scattering can be used to measure only chirally even quantities, whereas $h_1(x)$ is chirally odd and so to obtain information on $h_1(x)$ we must combine it with another chirally-odd observable. An example of such a function is the one needed to describe the azimuthal dependence of pions produced in deep-inelastic scattering. Therefore, one possible way to determine the transversity distribution is to use transversely polarized targets in combination with measurements of the azimuthal dependence of the produced hadrons.

A first hint of a non-zero transversity distribution has been reported by HERMES. In this experiment the single target-spin asymmetry for leptoproduction of pions was measured on a longitudinally polarized hydrogen target. The data show a small positive single-spin asymmetry. Similar data have been obtained on a longitudinally polarized deuterium target.

The data can be explained by a model calculation assuming reasonable estimates for both the transversity distribution $h_1(x)$ and the corresponding (chirally odd) fragmentation function. However, the small azimuthal asymmetry might also be caused by a final state interaction between the spectator system and the current quark jet. Future measurements using a transversely polarized target will be able to resolve this ambiguity, as the two processes give rise to a transverse single-spin asymmetry with different dependence on the azimuthal angle between scattering plane, transverse spin direction and plane of the produced hadron.

On the basis of the small asymmetries measured with longitudinally polarized targets, it is expected that sizable asymmetries will be observed if transversely polarized targets are used. Such experiments have recently been started at both COMPASS and HERMES. They will not only be able to measure the contribution of contaminating final-state interaction effects, but they will also allow the first direct measurements of the transversity distribution.

It should be emphasized, however, that considerably higher statistics will be needed to extract an accurate value for the tensor charge of the nucleon and to study the Q^2 dependence of the transversity distribution. Hence, although COMPASS and HERMES will provide very important first data in this otherwise virgin field, a full investigation of this aspect of nucleon structure can only be carried out at a new high-luminosity lepton scattering facility. Such a facility will make it possible for the first time to verify the predictions of QCD for the transverse spin structure of the nucleon, namely a large tensor charge and weak evolution of $h_1(x)$ with Q^2.

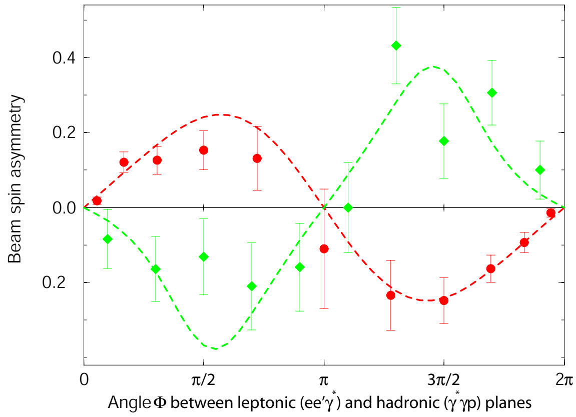

Figure 4.5: Beam spin asymmetry in the process $\vec{e}p \rightarrow ep\gamma$ from CLAS at JLab (red points) with electrons and from HERMES (green) with positrons, in somewhat different kinematical regions. The approximate $\sin\Phi$ dependence is suggestive of the applicability of the GPD formalism, as illustrated by the theoretical curves.

Generalised parton distributions

Generalized parton distributions (GPDs) offer a more comprehensive description of quark dynamics in the nucleon, since they can take account of correlations between different quark momentum states, and between longitudinal momentum and transverse position. They are universal non-perturbative objects entering the description of hard exclusive electroproduction processes such as $ep \rightarrow e'p + \gamma, \rho, \omega, \pi$. Using QCD factorization theorems, the amplitudes for such processes can be split into hard scattering amplitudes between partons and GPDs, as shown in Figure 4.1. From the theoretical point of view, the introduction of these new distributions builds a bridge between fundamental QCD, phenomenology and experimental observables. Moreover, such measurements are sensitive to the total angular momenta carried by quarks of given flavour in a polarized nucleon.

Several observables in deeply virtual Compton scattering (DVCS) and exclusive deeply virtual meson production (DVMP) provide a handle on the experimental determination of these distributions. However the hard production of photons within the target nucleon is indistinguishable from the Bethe-Heitler process in which the photons are emitted by the incident or scattered electrons. At high enough energies, DVCS is nonetheless expected to dominate in most of phase space, whereas at somewhat lower energies, the interference between the two processes may be used to study DVCS at the amplitude level.

The first experimental results do indeed indicate that Compton scattering at the parton level has been observed. Cross sections measured by the H1 and ZEUS collaborations at HERA are in qualitative agreement with estimates based on gluon and quark GPDs. Beam spin asymmetries, measured both at HERMES and JLab/CLAS (see Figure 4.5), display a characteristic $\sin\Phi$ dependence due to the above mentioned interference. Moreover, the first measurement of beam charge (e^+/e^-) asymmetry at HERMES is indicative of the anticipated $\cos\Phi$ dependence and identifies the role of $q\bar{q}$ configurations in the proton.

Dedicated DVCS experiments, using new additions to existing detectors, will be performed at JLab and HERMES starting in 2004. These will provide much better statistics and an improved separation of the exclusive process by detecting all final state particles. This allows the study of the scaling behaviour of observables, putting on a firm ground the underlying theoretical description. Looking further ahead, such measurements are among the primary goals of the 12 GeV upgrade at JLab. Measurements at COMPASS, with 100–200 GeV μ^+ and μ^- beams hold great promise for mapping out the t-dependence of the GPDs.

The cross sections and asymmetries for exclusive leptoproduction of vector and pseudoscalar mesons are sensitive to different combinations of GPDs. Hence data on the various reactions can lead to information on the distributions for different flavours. Of particular interest is the production of longitudinally polarized vector mesons on a transversely polarized proton target. In these processes, the transverse target asymmetry is sensitive to the contribution of the total angular momentum of the quarks, J^q, to the proton spin. Specifically, ρ^0, ρ^+ and ω electroproduction are sensitive to the combinations $2\,J^u + J^d$, $J^u - J^d$ and $2\,J^u - J^d$ respectively. Measurements of this kind were started at HERMES and COMPASS in 2002. With the 12 GeV upgrade, JLab/CLAS should be able to measure cross sections up to $Q^2 \sim 8$ GeV^2.

In order to fully exploit the potential of GPDs, a new lepton scattering facility is needed. Precise measurements of the associated deeply virtual and exclusive reactions require both sufficient beam energy and high luminosity. This will permit the dependence on different kinematic variables to be studied systematically, which is crucial for extracting the distributions from data. The existing facilities in Europe operate at luminosities that do not allow such studies. In the United States, the CEBAF accelerator will make a major step forward, but even when upgraded in energy to 12 GeV, it does not cover all of the necessary kinematical domain. Finally, further theoretical studies are needed to evaluate the role of higher-twist effects, as well as other possible applications of the GPD formalism.

Light-quark hadrons

At longer distances corresponding to the confinement scale of 1 Fermi and beyond, one cannot directly "see" quarks, but the underlying quark dynamics is nevertheless at the origin of ground-state properties of hadrons, their excitation spectrum and the interaction between them.

Our QCD-based understanding of such fundamental issues has been promoted significantly by recent high-precision measurements. In particular, results from MAMI on the neutron electromagnetic form factors and nucleon polarisabilities clearly indicate the importance of the pion cloud in the structure of the nucleon (see Section 4.2.4).

Strange elastic form factors of the proton have also been extracted from experiments on parity violation in electron scattering. The first results from JLab and MAMI suggest that the strange-quark content of the nucleon is small, as probed by vector currents. These results require further experimental and theoretical investigation.

The excitations of a quantum system can provide important information about the wave functions of its constituents. Modern precision experiments and detectors are shedding new light onto the old subject of baryon spectroscopy. For example, the recent determination of the quadrupole component in the electromagnetic $N \to \Delta$ transition (at MAMI, ELSA, LEGS and JLab) also points to the role of the pion cloud surrounding the nucleon.

Furthermore, sum rules directly connect low-energy properties to the polarized and unpolarized photoabsorption cross sections on the nucleon. In particular, the contribution to the Gerasimov-Drell-Hearn sum rule from the resonance region has been measured at MAMI and ELSA. The extension of such sum rules to the forward scattering of virtual photons will allow quantitative studies of the transition from a resonance-dominated description at lower Q^2 to a partonic description at larger Q^2. Such measurements are being carried out at ELSA, HERMES, MAMI and JLab.

The constituent quark model predicts more excited states of the nucleon than have been observed so far. The search for such states is a major thrust of many experimental programs in the years to come, and it will also require renewed theoretical analyses. Resonance decays such as $N^* \to N\pi\pi$ are being investigated in neutral channels at GRAAL and in charged channels at ELSA/SAPHIR and JLab/CLAS. Such experimental capabilities will be significantly enhanced in future with the use of the SLAC Crystal Ball at the upgraded MAMI and of the LEAR Crystal Barrel at ELSA. Similarly, studies of two-pion production in nucleon-nucleon collisions have been started at CELSIUS and COSY; these are sensitive to the properties and decays of the baryon resonance $N^*(1440)P_{11}$. The channel $N^* \to \Lambda K$, which can be studied at ELSA and Jlab, is also a promising one for the discovery of new baryon resonances.

Turning to the interactions of nucleons, detailed studies of proton-proton scattering have been performed as a continuous function of the beam energy at COSY/EDDA, with either unpolarized or polarized beam and target. These results significantly constrain nucleon-nucleon phase shift analyses up to 2 GeV and yield tight upper limits on the elastic widths of (hypothetical) narrow dibaryons.

Meson production dynamics in few nucleon systems may also reveal new features of the strong interaction. For example, η meson production at threshold in the 2, 3 and 4 nucleon systems already gives strong indications of the existence of a quasi-bound $\eta - He$ state. It will be the task of CELSIUS/WASA and COSY to search for more direct evidence for such a state.

Charmed quark systems

The importance of precision studies of the charmonium system, compared to the other quarkonia $s\bar{s}$ and $b\bar{b}$, relies on its privileged position, lying in the region of intermediate distances where the domains of perturbative and non-perturbative QCD come together. It is for this reason that the charmonium system provides a unique testing ground for QCD. Indeed, the masses and widths of the $c\bar{c}$ states directly reflect the basic $q\bar{q}$ interaction; the various terms in the interaction are connected with different specific features of the spectrum. Moreover, it is in charmonium spectroscopy where the gluon condensate of the QCD vacuum can be determined. Finally, from an experimental point of view, charmonium states below the $D\bar{D}$ threshold are limited in number, have small widths, and are well resolved.

Discovery of the missing levels and accurate measurement of all states will provide significant additional insights into QCD. It will help to differentiate among various QCD inspired potential models and to fill in blanks in our understanding of the basic $q\bar{q}$ interaction. Such a program is complementary to the physics of light-quark systems for which the large value of the strong coupling constant rules out the use of perturbation theory. At the other extreme, the spectroscopy of the bottomium system is characterized by the almost static behaviour of the very massive b quark.

Charmonium spectroscopy was extensively studied at e^+e^- colliders during 1974–80. However, the technique of studying charmonium via e^+e^- annihilation had important limitations. In particular, only the vector states, $J^{PC} = 1^{--}$ $(J/\Psi, \Psi', \ldots)$, could be directly formed, all other states having to be produced by radiative transitions from the J/Ψ or Ψ', with consequent limitations in precision. The masses of several states were well determined but not, in general, their widths.

Experiments R704 at CERN and E760/E835 at Fermilab demonstrated that charmonium formation using $p\bar{p}$ annihilation has two significant advantages compared to e^+e^- annihilation. The first is that, since $p\bar{p}$ annihilation must proceed via two or three intermediate gluons, it can lead to the direct formation of charmonium states with all possible quantum numbers. This means that the precision achievable for all states depends only on the quality of the antiproton beam and not on the detector properties. The second advantage comes from the possibility of cooling antiproton beams (stochastically and/or with electrons) to obtain a momentum resolution of one part in 10^5, which translates directly into improved mass resolution.

With this technique, impressive progress has recently been achieved in the determination of masses and widths of several states, including the χ_1 and χ_2 states, and the first observation of the h_c. The latter is the long awaited $^1P_1$ state whose mass can yield information about the spin-spin interaction between quarks.

Despite these efforts, there remain a number of unresolved fundamental questions concerning the charmonium system. These will be addressed by experiments focused on charmonium spectroscopy, using the PANDA detector system at GSI/HESR. This facility will offer improvements beyond the Fermilab program, by providing higher-energy antiproton beams (15 GeV), higher luminosity, better cooling, and a state-of-the-art hermetic detector for both electromagnetic and charged particles. Particular topics from its program are as follows:

- Little is known about the ground state $\eta_c(1^1S_0)$. Its first radial excitation $\eta_c'(2^1S_0)$ has only been hinted at in an early e^+e^- experiment and was not observed in $p\bar{p}$ experiments. A possible explanation for this non-observation might be a shift of the mass of $\eta_c(1^1S_0)$, due to a mixing with a nearby 0^{-+} glueball.
- The singlet P-wave resonance $h_c(^1P_1)$ is particularly important for determining the spin-dependent component of the confinement potential. Very little is known about this state so far.
- Essentially no states are known above the $D\bar{D}$ breakup threshold, so there are potentially significant new discoveries to be made. For instance, most of the d-wave states are still missing.
- Exclusive charmonium decays can provide a testing ground for QCD predictions, particularly for the study of higher Fock state contributions, which might produce sizeable effects in certain cases.

When running at full luminosity, HESR will produce a large number of D-meson pairs. Thus, it can also be regarded as a hadronic factory for tagged open charm. The high yield and the well-defined production kinematics of these pairs would allow studies of rare processes in the charm system such as CP-violation or flavour mixing, and determininations of the decay constants of charmed mesons. Measurements of CP-violation and rare D decays could open a new window into physics beyond the Standard Model.

Finally, it is worth mentioning the exciting signals reported by the SELEX Collaboration at Fermilab, which hint at the first observation of three doubly charmed baryon states. The study of these systems, whose existence is required by broken $\mathrm{SU}(4)_f$ symmetry, is an experimental challenge because of the very low cross sections and small branching ratios.

4.2.4 The low-energy frontier and chiral dynamics

Chiral symmetry and hadron physics

The chiral symmetry present in QCD is spontaneously broken. As a consequence there is a set of light particles, called Goldstone bosons, whose interactions are strongly constrained by this symmetry. Even though the underlying QCD interactions which cause spontaneous symmetry breaking are strong, Goldstone bosons interact weakly at low energies. In fact, in the limit of massless quarks and zero energy, their interactions strictly vanish. This makes it possible to build an effective field theory with a well defined expansion in powers of energy, momentum and quark masses: chiral perturbation theory.

During the last decade major progress has been made in applications of chiral perturbation theory and comparisons with accurate low-energy experiments. Precise measurements of $\pi\pi$ scattering near threshold at the Brookhaven National Laboratory and the detailed theoretical analysis of these data have settled the question of the quark condensate in the limit of vanishing up and down quark masses. Further advances can be expected from studies of pionic bound states with the DIRAC experiment at CERN. Given the high precision that both experiment and theory have now reached, the inclusion of electromagnetic radiative corrections becomes an important task. This will demand close collaboration between theory and experiment in order to succeed.

Over the next decade improvements are also foreseen in the three-flavour sector, which includes strange quarks. Many processes involving kaons and η mesons have now been systematically analysed. Such studies will allow examination of the dependence of low-energy QCD dynamics on the number of flavours. They could also indicate whether the pattern of spontaneous chiral symmetry breaking remains the same in the presence of strange quarks. It is therefore important to investigate as many observables as possible that depend strongly on the strange quark mass. Examples of these are the study of η decays at WASA/CELSIUS in Uppsala and KLOE/DAΦNE in Frascati. More precise measurements of various electromagnetic and semileptonic decay form factors of the charged and neutral kaons will provide strong tests. Differences between kaon and eta properties and the equivalent pion ones can also yield important clues. Strange-quark mass effects on pionic observables can be studied in this way, providing a direct equivalent of measurements of the strangeness content of the proton.

Significant progress is also expected from the pionic hydrogen measurement at PSI and the DEAR experimental programme at DAΦNE. One of the goals of DEAR is to measure the energy shift and width of the K_α line in kaonic hydrogen with a precision at the percent level. This will provide a new degree of accuracy in our understanding of the low-energy kaon-nucleon interaction.

Structure of the nucleon

Many new insights have been gained from high-precision experiments exploring the low-energy structure of the nucleon and its pion cloud, primarily with electromagnetic probes. The significant observables can be roughly grouped into three classes, for which we summarise a few recent highlights:

- Ground state properties
  These are in particular form factors and polarisabilities. At the Mainz Microtron MAMI, the Bates Linear Accelerator Center in the U.S. and the Amsterdam Pulse Stretcher (AmPS), the magnetic and electric form factors of the neutron have been measured over the last years in the momentum range $Q^2 < 1$ GeV^2. These results hint at the importance of the pion cloud in the structure of the nucleon and represent a constraint for chiral dynamics. Also at MAMI precise values have been obtained from Compton scattering of real photons ($Q^2 = 0$) for the electric and magnetic polarizabilities, as well as generalized polarizabilities (at $Q^2 > 0$) from the $p(e, e'p)\gamma$ reaction. These results have set strong constraints on QCD-inspired models.

- Baryon resonances
  Meson decays and in particular electromagnetic transition rates can provide decisive information on the wave functions of the constituents of hadrons. The recent determination of the quadrupole component in the $N \rightarrow \Delta$ transition has already been mentioned in Sec. 4.2.3. A particularly informative method for investigating the resonances of the nucleon is the determination of absorption cross sections in separated decay channels, using circularly polarized photons on polarized protons. This is relevant to the Gerasimov-Drell-Hearn (GDH) sum rule. The GDH collaboration at MAMI and ELSA could measure these cross sections for the first time, providing insight into the first ($\Delta(1232)P_{33}$), second ($N(1520)D_{13}, N(1535)S_{11}$) and third ($N(1680)F_{15}$) resonance regions of the nucleon. The detector SAPHIR at ELSA allowed new studies of hyperon resonances and saw indications of a new resonance in the ejectile asymmetry.

- Meson production at threshold
  Meson production at threshold provides particularly good tests of soft-meson physics and chiral perturbation theory. The description of the production of pions from the nucleon in the $p(\gamma, \pi^0)N$ reaction at MAMI was a triumph for chiral perturbation theory. It showed that the low-energy theorem based on tree-level diagrams gave an E_{0+} amplitude about a factor 2 too large, whereas the next-order loop correction could reproduce the observed amplitude. Similar results have

also been obtained for the p-wave amplitudes and the Coulomb amplitude L_{0+}.

The power of precision studies using electromagnetic probes at low momentum transfer as described above has been demonstrated by the experiments at MAMI and ELSA. The challenges posed for the next ten years lie in the further improvement of the precision and the selection of the most significant observables. The first is an experimental challenge, whereas the second calls for collaboration between theorists and experimentalists.

At the Mainz Microtron MAMI the maximum energy will be increased from 855 MeV to about 1.5 GeV. This will be accomplished by the addition of a fourth double-sided harmonic microtron stage to the existing cascade of three “race track” microtrons. The construction of this extension is well underway and the commissioning of the upgraded machine is planned for mid 2004. In order to take full advantage of this upgrade two major new experimental equipments will be installed: the SLAC Crystal Ball and the GSI forward magnetic spectrometer (KAOS@MAMI).

The installation of the Crystal Barrel detector and the TAPS photon detector wall at the ELSA stretcher ring in Bonn make this a unique facility for studying the electromagnetic coupling of baryon resonances. In particular, it can explore the energy region $1.5 < E_\gamma < 3.5$ GeV which cannot be covered by MAMI.

Chiral dynamics in nuclear systems

The existence of the mass gap in the spectrum of light hadrons and its possible connection with the spontaneously broken chiral symmetry of QCD raises an important issue: how do properties of hadrons and their mass spectra evolve with changes of thermodynamic conditions? This is one of the driving motivations for the use of high-energy heavy-ion collisions to study matter at high densities and temperatures [3].

Related questions of particular interest concern the interactions of a Goldstone boson with the nuclear medium. Accurate data from a GSI experiment on $1s$ states of negatively charged pions bound to Pb and Sn isotopes have recently revived this discussion and its implications for in-medium chiral dynamics. Such experiments will be pursued further and extended to searches for quasi-bound nuclear states of kaons and η mesons.

4.2.5 QCD and nuclear matter

Apart from the low-energy aspects just mentioned, there are specific QCD phenomena related to the propagation of high-energy particles in matter to which we now turn our attention.

Colour transparency

Quantum Chromodynamics not only provides a highly successful description of strong-interaction phenomena at high energies, but it also leads to several remarkable predictions for the interaction of strongly interacting particles traversing dense nuclear matter.

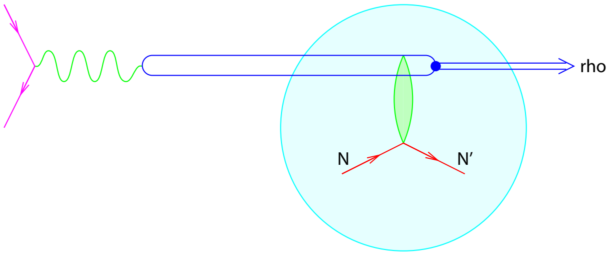

Figure 4.6: The interaction of a $q\bar{q}$-fluctuation of a virtual photon with a nuclear target. If the interaction of the $q\bar{q}$-fluctuation is reduced as compared to the normal hadronic interaction, colour transparency is said to occur. At the same time the Q^2-dependence of the length of the hadronic fluctuation (i.e. the coherence length) may mimic colour transparency effects.

An explicit example is provided by the interaction of a $q\bar{q}$-pair (originating from the hadronic structure of a virtual photon) with a nuclear target. At high enough Q^2 the $q\bar{q}$-pair can be assumed to have a small transverse

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[3] See section 5.4 in the chapter on Phases of Nuclear Matter.

size and so it acts as a (white) color dipole interacting only weakly with the neighbouring nucleons (see Figure 4.6), an effect known as Colour Transparency (CT). Although this striking QCD phenomenon was predicted twenty years ago, the first evidence for it emerged only recently and further experimental investigation is needed.

One of the difficulties in finding unambiguous evidence for colour transparency is the fact that other effects may resemble the anticipated reduced interaction effects. If the Q^2 dependence of ρ^0 vector meson production on nuclei is considered, for instance, the observed transparency will not only be governed by the possible occurance of colour transparency, but as well by the duration or length of the hadronic fluctuation (see Figure 4.6). Since the corresponding coherence length is inversely proportional to Q^2, an increase of Q^2 shortens the coherence length, reducing the strong interactions of the fluctuation and thus mimicking the effect of colour transparency.

Nevertheless, in recent years new experimental evidence supporting colour transparency has been collected: (i) the observed A-dependence of 2-jet production in a pion induced experiment (E791 at FermiLab) at $E_\pi = 500$ GeV ($A^{1.61\pm0.08}$) is in agreement with the CT-based prediction ($A^{1.54}$); (ii) the slope of the t-dependence of vector meson production measured at HERA shows the expected reduction with Q^2 ('shrinkage'), albeit with poor statistics, and (iii) the Q^2 dependence of of coherent ρ^0 production on ^{14}N in fixed coherence-length bins observed at HERMES shows a constant rise which is consistent with the prediction based on colour transparency.

Despite the recent progress, more data are needed to fully establish this QCD prediction. Further experimental studies to test the colour transparency hypothesis are foreseen at HERMES and at COMPASS, where it will be possible to extend the kinematic range of the measurements. Moreover, at COMPASS it will be possible to separate transparency effects for longitudinal and transversely polarized virtual photons.

Parton propagation in matter

The energy loss dE/dL experienced by partons propagating through nuclear matter is an important issue. Experimental information on parton energy loss in (cold) nuclear matter can be obtained from semi-inclusive deep-inelastic scattering on heavy nuclei. By comparing the hadron yield per DIS event on nuclei to the same yield on deuterium, an (energy dependent) attenuation will be observed. This hadron attenuation can be related to the energy loss of the propagating parton and the length of its trajectory, or – in other words – the time it takes before the hadron is formed.

Existing knowledge about the parton energy loss and hadron formation times is extremely limited. However, it would be very interesting to obtain experimental information on these quantities since they represent fundamentally new knowledge of composite systems of quarks and gluons. Moreover, quantitative information on the parton energy loss in matter and hadron formation times is needed for the interpretation of relativistic heavy ion collisions, which it is hoped will provide evidence for a new state of matter: the quark-gluon plasma.

Experimental information on parton propagation effects in matter can be obtained by embedding the hadron formation process in a nucleus, as depicted in Figure 4.7. In the nucleus, the produced hadron will reinteract with the surrounding nucleons, and as a result fewer hadrons will be produced. The reduction in the observed number of hadrons depends on both the parton energy loss and the hadron formation time. Hence the ratio of the number of hadrons produced on a heavy nucleus to that on deuterium can provide information on these quantities.

Experimental information on hadron attenuation in various nuclei has recently been obtained by the HERMES experiment at DESY. The ratio of hadrons produced on ^{14}N (or ^{84}Kr) and ^{2}H (normalized against the number of deep-inelastic scattering events in each case), was measured as a function of the fraction of the energy transfer carried by the observed hadron.

As this fraction increases, the data show a decrease of the rate of hadrons produced in nitrogen (or krypton) relative to deuterium. Qualitatively this implies that fast hadrons have a relatively short formation time, leading to a relatively strong reduction of the ratio.

The data are well described by QCD-inspired calculations if a value of $dE/dL \approx 0.3$ GeV/fm is taken for the partonic energy loss in cold nuclear matter. This value can be compared to the energy loss of 0.25 GeV/fm derived from recent PHENIX data on π^0 production in Au+Au collisions at $\sqrt{s} = 130$ GeV. If the PHENIX number is converted to a corresponding energy loss in the initial hot stage of the Au+Au collision, a value of about 5 GeV/fm is found. Comparing this number for hot nuclear matter with the value derived from the HERMES data for cold nuclear matter, it can be seen that the gluon density (which drives the energy loss) is possibly an order of magnitude larger in the initial phase of the Au+Au collision. This result reflects a new synergy between two fields that used to be essentially independent: relativistic heavy-ion collisions and deep inelastic scattering.

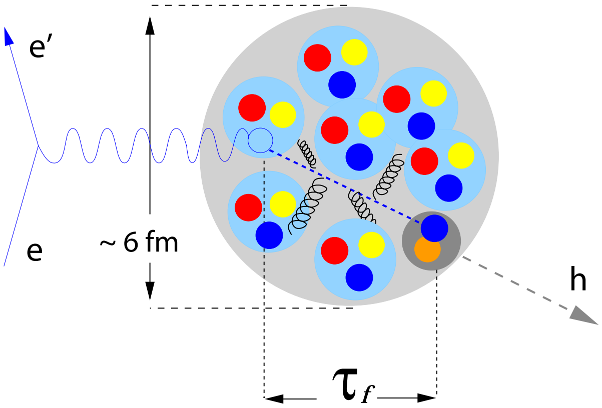

Figure 4.7: Hadron formation in deep-inelastic electron scattering from a nucleus. A quark in one of the nucleons is hit, resulting in the formation of hadrons. Due to parton energy loss and hadron rescattering the number of hadrons observed will be reduced compared to the free case.

The few available data show the potential of this new field at the interface of deep-inelastic scattering and relativistic heavy-ion collisions. Systematic data on a range of nuclei are necessary for an in-depth study of parton propagation effects in matter. High statistics are needed to explore the various kinematic dependences independently, and to test QCD predictions for the parton energy loss in nuclear matter. Moreover, such measurements will make it possible to carry out studies of flavour dependence by comparing data for various hadron types (π, K and p).

Strange and charmed quarks in matter

An ordinary nucleus is a many-body system composed of protons and neutrons. When one or more hyperons are implanted in the nuclear medium a new quantum number, strangeness, is added to the nucleus, thereby opening a new dimension to the nuclear chart. Hypernuclear physics merges isospin and strangeness into the enlarged field of flavour $SU(3)$ many-body dynamics. The main emphasis is on the non-perturbative dynamics of u, d, and s quark systems at finite density as realized by protons, neutrons and hyperons in a nucleus close to the ground state.

These exotic nuclei provide a variety of new and exciting perpectives, ranging from the exploration of nuclear structure via the single-particle behaviour of hyperons in the nucleus to the study of the baryon-baryon strangeness changing weak interaction, which can be addressed only in the non-mesonic weak decay of hypernuclei. They can also aid the experimental study of hyperon-nucleon interactions which are, at present, still poorly known. Moreover, the study of basic properties of hyperons and strange exotic objects like the hypothetical H-particle, which is of fundamental importance for the understanding of QCD, can also be addressed with hypernuclei.

Hypernuclear physics has made significant progress in the last fifteen years, mainly at BNL, KEK and COSY where it has drawn the attention of a large community. Experimental studies on hypernuclei are continuing at different laboratories in the USA (JLab and BNL), in Japan (KEK), and in Europe using the DAΦNE machine at Frascati National Laboratory.

At DAΦNE the FINUDA experiment will exploit low-energy (16 MeV) K^- particles from ϕ decay to produce large numbers of Λ-hypernuclei by the (K^-_{stop}, π^-) reaction on several nuclear targets. The momentum transfer involved is such that the whole spectrum of allowed hypernuclear states will be populated. The good energy resolution of 750 keV for nuclear levels, twice as good as the best so far, will lead to a substantial step forward in hypernuclear spectroscopy. Starting in 2003, FINUDA will take data for the following three or four years. Its main goal will be to study with unprecedented precision the weak reaction $\Lambda N \to NN$ which can occur only in a nuclear medium. This process gives basic insights into the strangeness changing baryon-baryon weak interaction.

For the future, kaon beams with intensities one order of magnitude larger than presently available could be provided by the Japanese Hadron Facility (JHF). A hypernuclear physics program is also foreseen in the context the HESR project at GSI. This can lead to a detailed spectroscopic study of singly and multiply strange hypernuclei produced in collisions of antiprotons with nuclei.

Hypernuclei are the first examples of exotic *flavoured* nuclei. The investigation of charmed hypernuclei, containing a charmed baryon, is an interesting option of the physics programme of HESR at GSI. The lightest mesons carrying charm $C = \pm 1$ are the $D^{\pm,0}$ states with a mass of about 1865 MeV, while the spectrum of charmed baryons starts with the Λ_c^+ at about 2.3 GeV. So far nothing is known about charmed nuclei and hence experimental studies of such systems offer new insights into the dynamics related to breaking of $SU(4)$ flavour symmetry by the large mass of the charmed quark.

Another novel item in the scientific programme covered by PANDA at HESR/GSI will be the study of D-mesons interacting with a nuclear medium. The D-meson is the prototype of a heavy-light quark-antiquark system in QCD, so this project offers unique possibilities for exploring a single, localised light quark interacting with nucleons in a nucleus and for investigating the resulting change of the D-meson mass in matter.

4.3 Outlook

The topics described in this Chapter demonstrate that the study of QCD and the structure of hadrons is entering a new phase. Much new high-precision data will become available in the near future from existing facilities. These experimental developments must be accompanied by similar theoretical efforts. Considerable progress can be expected on a timescale of five to seven years. However, it is also clear that many of the questions outlined here will remain unanswered without new experimental facilities. On the basis of such considerations the following list of recommendations has been prepared.

- **Maintain – and expand where necessary – the infrastructure for adequate theoretical support in the field of QCD.**
  In particular, young theorists must be encouraged by creating an adequate number of positions for this area of physics. Also, further substantial investments in computational infrastructure are required for large-scale lattice QCD calculations.

- **Exploit the current European frontier facilities in our field – including modest upgrades where appropriate – until they are surpassed by new facilities.**
  The unique deep-inelastic scattering facilities at CERN (COMPASS) and DESY (HERMES-II) especially should be fully exploited through measurements of the gluon polarization, generalized parton distributions and transversity distributions. At somewhat lower energies, the ϕ factory at Frascati (DAΦNE) and the new lepton beam facility at Mainz (MAMI-C) will provide competitive measurements of meson and baryon structure, respectively. Lastly the existing facilities in Bonn (ELSA), Grenoble (GRAAL), Juelich (COSY) and Uppsala (CELSIUS) are expected to provide important data on various hadronic channels.

- **Prepare for the construction of the High-Energy Storage Ring (HESR) at GSI.**
  The planned GSI International Accelerator Facility for Beams of Ions and Antiprotons has been approved and will play a crucial role in promoting our understanding of the physics of the strong interaction. This facility will provide 1.5–15 GeV/c (cooled) anti-proton beams impinging on fixed (internal) targets. It will make possible searches for new charmonium states including hybrids ($c\bar{c}g$) and also for glueballs, while improving our knowledge of other states. It will also open new perspectives for exploring interactions of charmed hadrons with nuclear systems. It is strongly recommended that Europe-wide joint activities be directed toward the construction of HESR and its general-purpose detector system PANDA.

- **Prepare a full proposal for a high-luminosity lepton scattering facility.**
  This will be the new frontier QCD facility in the second decade of the 21st century. Experiments at such a facility will provide precision tests of several QCD predictions for aspects of hadron structure not dominated by gluonic contributions. These include transversity distributions and generalised quark distributions, as well as their evolution with Q^2*. The proposal could be based on several recently prepared documents which describe how such a project could be incorporated in either existing or planned large-scale accelerator facilities in Europe and in the United States.*

- **Continue and further develop international world-wide collaboration in the field of QCD.**
  European participation in new large-scale projects in both the USA and Japan is encouraged. The exchange of ideas, instrumentation and personnel between the EU, the USA and Japan will stimulate progress. Moreover, the complementarity of proposals for projects around the world will ensure a healthy competition without unnecessary overlaps.

5. Phases of Nuclear Matter

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5.1 Introduction

Exploring the nuclear-matter phase-diagram and identifying its different phases is one of the main challenges of modern nuclear physics. The fundamental endeavour is to understand at the various energy scales the properties of the nuclear interaction and its macroscopic manifestations. At low energy densities, hadronic bound states are the degrees of freedom of nuclear matter. Their interaction is described by an effective theory emerging as the low energy limit of Quantum Chromodynamics (QCD), the fundamental theory of strong interactions. At higher energy densities, the degrees of freedom of nuclear matter are quarks and gluons, interacting via the strong force.

To explore the phase diagram at energy densities ranging from a few MeV up to several hundreds of MeV and matter densities extending up to many times the normal density, heavy-ion collisions are exploited to heat up and compress nuclear matter. The kinetic energies of the collisions range from the Fermi energy scale, $\mathcal{O}(100A$ MeV), through relativistic energies $\mathcal{O}(1A$ GeV) to ultra-relativistic energies up to $\mathcal{O}(1A$ TeV) of the future LHC collider.

The strong interaction, responsible for the cohesion of matter, has been extensively studied in the ground and excited states of the nucleus. To gain a deeper insight into the properties of the nuclear interaction, nuclei are excited up to a point where they dissociate into loosely interacting nucleons. The objective of heavy-ion physics at the Fermi energy is, in this context, to establish the properties of the phase transition from the self-bound state inside the nucleus to a gas of freely streaming nucleons.

The equation of state (EOS) of nuclear matter determines the dynamics of heavy-ion collisions and stellar processes, such as supernovae explosions. Compressibility characterizes the ability of nuclear matter to withstand the gravitational pressure. It also defines the maximum mass a neutron star can sustain prior to collapsing into a black hole. This motivates to explore the EOS at 2-5 times the ground-state density and nonzero energy density. In this region, the EOS is governed by the in-medium properties of baryons and mesons.

The focus of the research in the ultra-relativistic energy regime is to study and understand how collective phenomena and macroscopic properties, involving many degrees of freedom, emerge from the microscopic laws of elementary particle-physics. Specifically, heavy-ion physics addresses these questions in the sector of strong interactions by studying nuclear matter under conditions of extreme temperature and density. The most striking case of a collective bulk phenomenon predicted by QCD is the occurrence of a phase transition to a deconfined chirally symmetric state, the quark gluon plasma (QGP).

In the following, we first summarise the current understanding of the phase diagram of nuclear matter. We then review, for the various energy scales, the progress achieved since the previous Long Range Plan, and we address the implications and requirements for the future of the field.

5.2 The phase diagram of nuclear matter

The phase diagram of low temperature and dilute nuclear matter. The short-range property of the nuclear interaction and its similarity with the Van der Waals interaction suggests that nuclear matter inside the nucleus can be described as a liquid and undergoes a first-order phase-transition (Figure 5.1) at a given temperature. Several effects, such as those generated by the Coulomb or three-body forces, by the isospin dependence of the interaction and by correlations or clusterizations, might modify this ideal behaviour.

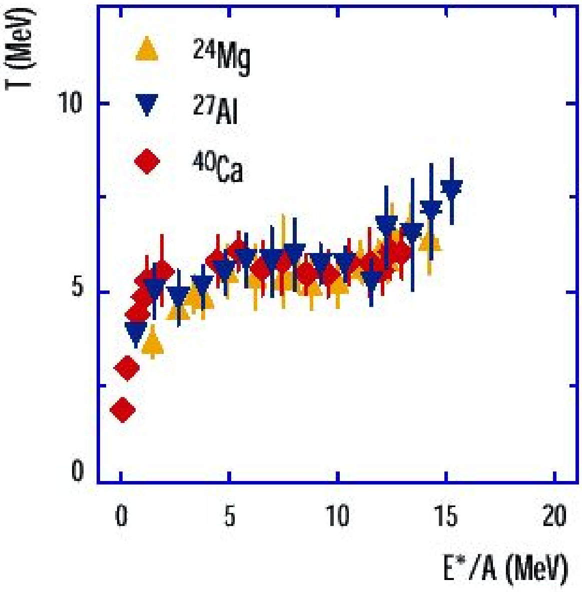

Figure 5.1: The caloric curve calculated for various nuclei. The model confines the nucleus, described by an anti-symmetrised combination of independent nucleon wave-packets, in an harmonic potential well. The plateau in the excitation energy dependence of the temperature is reminiscent of a first-order liquid-gas phase-transition.

When studied in nuclei, because of the finite size, a first order phase transition manifests itself through peculiar observables, such as negative micro-canonical heat capacities or the occurrence of large fluctuation in the partitioning of extensive quantities such as the energy.

For charge asymmetric systems the phase transition occurs in a two fluid (neutrons and protons) system which might lead to a richer phenomenology involving up to two densities as order parameters. The isospin dependence of the EOS is essential, for example, for the modelling of neutron stars.

The QCD plasma phase at vanishing baryon density. The most reliable approach to the thermodynamic behaviour of equilibrated quarks and gluons is *ab initio* computer simulations of lattice-regularised QCD at finite temperature. These computer "experiments" support the expectation that strongly interacting matter undergoes a phase transition in which chiral symmetry is restored and quarks and gluons are deconfined, two different non-perturbative aspects of the QCD vacuum, which occur at exactly the same critical temperature.

For the QCD plasma state at vanishing baryochemical potential, significant theoretical progress was made (Figure 5.2) in recent years in localising the critical temperature ($T_c = 175 \pm 15$ MeV) of the phase transition and characterising properties of the high-temperature plasma phase. The phase transition between the hadronic and plasma phase is most likely a rapid cross over which happens in a narrow temperature interval of about 20 MeV. The associated change of the energy density by $\Delta\varepsilon/T_c^4 \simeq 8$ may be interpreted as latent heat of the transition.

Recent lattice calculations also give access to properties of bound states immersed in the thermalised medium. For example, direct studies of spectral functions now confirm the in-medium modification of light hadron properties, previously deduced from the behaviour of hadronic screening masses and susceptibilities. Detailed lattice simulations of the temperature dependence of the heavy quark potential confirm that $c\bar{c}$-bound states of separation similar to the J/ψ ($r_\psi \sim 0.2$ fm) will already dissolve close to T_c, where their bound state energy ~ 500 MeV becomes compatible with the average thermal energy of gluons, $\sim 3\,T_c$. The dissociation temperature of tighter bound ($b\bar{b}$) heavy quark pairs is expected to lie well above T_c but within the temperature range accessible to LHC. The determination of the characteristic temperature-

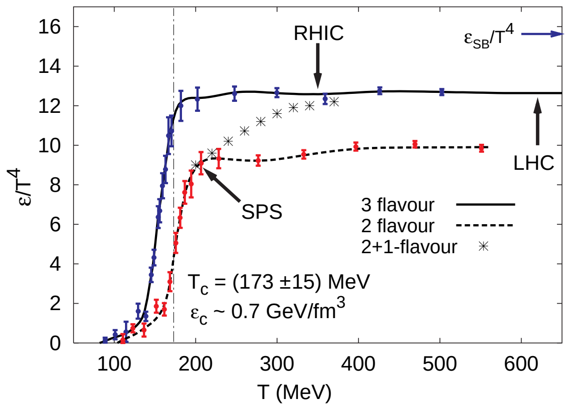

Figure 5.2: The energy density calculated in QCD thermodynamics on the lattice at zero baryochemical potential, considering two (red symbols) and three (blue symbols) of degenerate quark flavors as well as the physically realised quark mass spectrum (stars) of two light and one heavier (strange) quark. Arrows indicate estimates of the initial temperatures attained in heavy ion collisions at SPS, RHIC and LHC. The value of the Stephan-Boltzmann limit for the energy density of an ideal quark–gluon gas is given on the right-side ordinate.

dependent dissociation pattern of the families of heavy-quarks bound-states can, however, only come from experiment. This calls for the further experimental study of charmonium production in heavy-ion collisions at *all* available bombarding energies and strongly motivates the characterisation of bottomonium states in nucleus-nucleus collisions – a physics topic for which the LHC will be unique.

The phase diagram at finite baryon density. At finite baryon-number density (baryochemical potential $\mu_B \neq 0$), the standard Monte-Carlo sampling techniques are not applicable. Recent theoretical progress (Figure 5.3) overcomes this problem and extends lattice simulations of the QCD phase transition for values of the baryochemical potential up to $\mu_B = 500 - 800$ MeV. Remarkably, the critical temperature decreases very mildly with increasing baryochemical potential. Thus, statements made previously on the basis of $\mu_B = 0$ lattice simulations seem to apply not only at the LHC but also at RHIC ($\mu_B \sim 50$) and even for $\mu_B \sim 250$ attained at the highest SPS energy.

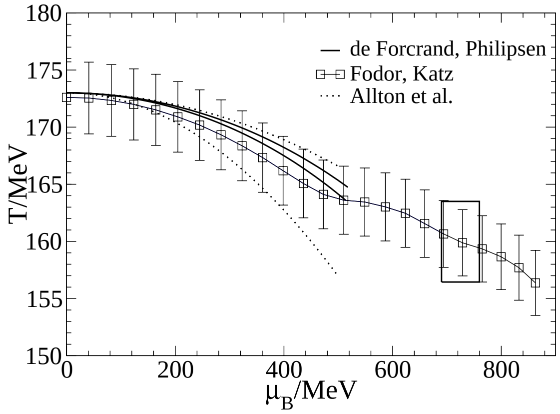

Figure 5.3: First lattice results for the QCD phase diagram at finite baryon chemical-potential. The lines indicate a rapid cross-over transition at low μ_B which become first order above the tri-critical point. The position of this tri-critical point (indicated by the rectangle on the figure) is subject to significant uncertainties.

At increasing baryochemical potential, extracted fireball freeze-out temperatures fall substantially below the expected critical temperature. In this region, which can be populated in heavy-ion reactions at energies of $\mathcal{O}(10A$ GeV), we observe a dense interacting resonance gas. The strong coupling of mesons and baryons through resonance excitation leads in that case to a modification of spectral functions of these states. Moreover, it was conjectured more than a decade ago that the chiral condensates should be substantially reduced inside such a nuclear medium. An observable consequence would be a modification of the mass of hadrons as they are imbedded inside nuclei.

At very high baryon densities and low temperature effective field theories are expected to describe the QCD phase diagram. Quark matter is known to be a colour superconductor at very high baryon density. Quarks form Cooper pairs due to an attractive interaction in the colour-anti-triplet channel. The properties of the colour-superconducting state depend on the number of quark colours and flavors involved in the pairing process. Besides these *conventional* asymmetry term superconducting states, more exotic forms of pairing have also been suggested.

An example is the analogue of the Larkin-Ovchinnikov-Fulde-Ferell state known from condensed matter physics, which leads to a crystalline structure in the colour superconductor. The study of this rich structure of the QCD phase diagram at high density can presently be addressed only through theoretical experiments which will require a sizable upgrade in computer resources devoted to theory.

5.3 Nuclear collisions at the Fermi energy: the liquid - gas transition

Similarly to macroscopic systems, in a finite system, such as the nucleus, phase transitions manifest themselves by abrupt transformations of the matter properties. Indeed rapid modifications, reminiscent of the liquid-gas phase transition, have been identified in heavy-ion collisions around the Fermi energy. At excitation energies approaching $3A$ MeV, the nuclear system fragments into intermediate-mass nuclei, an observation correlated with the abrupt end of binary fission and the disappearance of heavy evaporation-residues. Simultaneously, the suppression of collective vibrations is observed (disappearance of the Giant Dipole Resonance in the photon spectrum) and the fragmenting system is subject to a collective radial expansion. At excitation energies exceeding $10A$ MeV the system vaporises into mainly protons and neutrons.

Through recent progress in experiments, by careful selections of the final state, and in theory, by understanding thermodynamics in finite system, novel observables have been defined to confirm the occurrence of a phase transition, identify its order and locate its position in the phase diagram. Exploiting the isospin dependence of the EOS offers yet another observable, still under investigation, of the phase transition.

Decoupling observables related to the dynamics of the collision from those related to the thermodynamics properties of nuclear matter, is a key issue we shall survey next.

Dynamics and thermodynamics. In absence of an exact description of the nuclear many-body problem, comparison of models with experiments to extract the EOS leads to ambiguities. One way to progress consists of selecting experimental conditions in which well identified signals probe specific transport properties (compressibility, viscosity, ...). The neck emission of fragments observed in dissipative binary collisions as the result of combined bulk and surface instabilities provides such conditions. However, since several models, based on very different dynamical assumptions, successfully describe multi-fragmentation observables, it was suggested that the dynamics is dominated by few global properties. The statistical treatment of the remaining information might then be justified. Based on this assumption a second approach requests selecting classes of events for which the dynamics are controlled by a few collective variables (mass, excitation energy, expansion volume and velocity, spin, quadrupole deformation ...), all the other degrees of freedom being statistically distributed. It assumes that the reaction is complex enough so that only few global variables have a non trivial dynamics while the remaining available phase space is randomly populated. The statistical prescription then applies.

Caloric curve. The experimental observation of the temperature saturating over a broad range of excitation energy was presented as evidence for a phase transition in nuclei (see previous NuPECC Long Range Plan report). The use of several thermometers exploiting very different observables has confirmed this observation (Figure 5.4) of a rapid increase of the excitation energy over a narrow temperature range. Such a consistency has resulted from an intense modelisation effort in which effects (excluded volume of fragments forming the real fluid, radial expansion of the system, decay of excited primary fragments, collisional life-time ...) modifying the apparent temperatures have been unfolded. The measured value of the saturating temperature changes with the mass of the fragmenting system indicating that Coulomb instabilities might trigger the phase transition in finite systems.

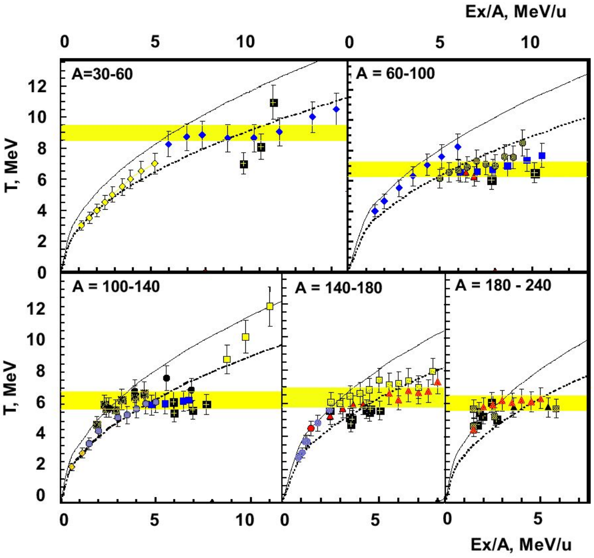

Figure 5.4: Caloric curves (different symbols represent results from different thermometers) measured for fragmenting systems with various masses. The shaded band indicates the value of the saturating temperature which shows a mass dependence in agreement with the onset of Coulomb instabilities.

Negative heat capacity. Progress in various fields of physics have recently shown that in a constant-energy ensemble (micro-canonical) negative values of the heat-capacity define a first order phase transition. The heat capacity can be deduced from the measurement of the kinetic-energy fluctuation. Negative values result in anomalously large fluctuations. The existence of a negative heat-capacity (Figure 5.5) was observed in the excitation-energy range between 3 and 6 MeV, providing the most direct indication of a first order liquid-gas transition.

Isospin distillation. The theory of phase transitions in two-fluid systems predicts different N/Z concentration in each phase: the liquid phase drives the system toward symmetric matter while the gas phase absorbs the isospin. This property can be verified by measuring in the final state of neutron rich systems the enhanced population of ^3H with respect to ^3He isotopes. Since the isovector part of the nucleon-nucleon interaction at sub-saturation densities favours particular N/Z concentrations in the fragments, the experimental determination of the isospin distribution will constrain the properties of the symmetry term of the nuclear EOS in the low density regime.

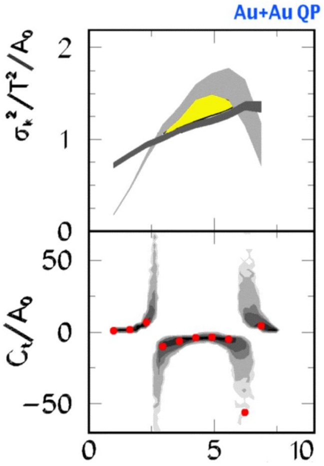

Figure 5.5: Study of the partitioning of the Au quasi-projectile excited in a Au + Au peripheral reaction at 35A MeV. Top: Event-by-event fluctuations of the kinetic energy in the fragmenting system measured as a function of excitation energy and compared to the kinetic heat-capacity deduced from the slope of the temperature dependence with the events averaged kinetic-energy. Bottom: Heat capacity calculated from the measured kinetic-energy fluctuations and kinetic heat-capacity.

Additional signals. Event-by-event fluctuations of order parameters are much smaller ($\sigma_p^2 \sim \langle p \rangle$) for an ordered phase, such as a liquid, than ($\sigma_p^2 \sim \langle p \rangle^2$) for a disordered phase, such as a gas. This has indeed been observed in the measured fluctuation of the Z_{max} distribution, the change occurring at excitation energies of the order of 7A MeV, providing a possible measurement of the energy at which the liquid-gas coexistence ends.

Dynamics of the phase transition: Spinodal decomposition The existence in the nuclear liquid-gas phase of a region of mechanical instability, called the spinodal region, disaggregates the nuclear system in many fragments if, during the heavy-ion reaction, it stays long enough in this unstable region. Stochastic mean-field approaches of the heavy-ion reaction dynamics indicate that, due to the short range of the nuclear interaction, the spinodal decomposition produces fragments of nearly identical size and with a charge $Z \approx 12 - 15$. This original partition is however largely modified by the subsequent collision dynamics. Nevertheless, a fossil signal was found (INDRA collaboration) in correlation measurements of the fragments distribution as a weak enhancement in the partition of equal size fragments of average charge equal to 15.

Chronometer of the fragmentation. Thermal photons, produced through neutron-proton bremsstrahlung while the nuclear system is thermalizing, provide a measure of the maximum temperature reached by the system and of the duration (Figure 5.6) of the thermalizing phase before it breaks into fragments. A sudden drop of the duration is observed (TAPS collaboration) at a temperature of about 6 MeV. It has also been (MEDEA-MULTICS collaboration) observed that the thermal photon multiplicity is anti-correlated with the production of fragments. These two observations are interpreted by the onset of multi-fragmentation which quenches the production of thermal photons. The same argument can be used in understanding the disappearance of the Giant-Dipole Resonance.

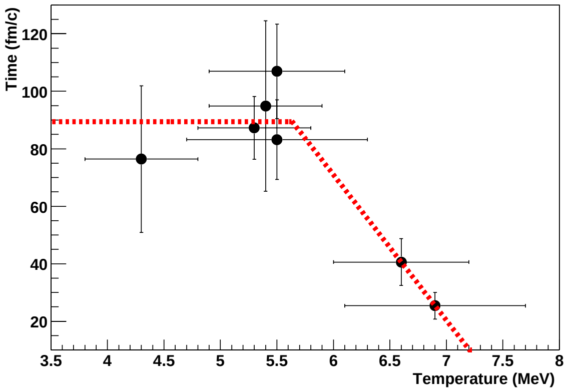

Figure 5.6: Duration of the thermalizing system deduced from the thermal-photon multiplicity, measured in heavy-ion collisions at various energies and for various entrance channels, as a function of the temperature deduced from the slope of the thermal-photon spectrum.

Outlook. Any progress in the understanding of the collision dynamics will require a complete characterisation of the events allowing their sorting and the identification of the pertinent information. This is presently not within reach in a fully unbiased way. New multi-detectors with isotopic identification up to large-mass elements, with neutron and photon detection, and with complete calorimetry capabilities are required. The availability of stable heavy-ion beams with energies around the Fermi energy is needed over extended time periods. A strong theoretical effort must accompany the experimental programme. It must include the development of dynamical description of nuclear reactions and the analysis of the dynamical population of statistical ensembles.

The physics of the liquid-gas phase transition, in particular, and of phase transitions in general must be reconsidered when applied to small finite systems. The theoretical effort must be accompanied by an as intense experimental work to exploit all the resources offered by the fluctuation and correlation analysis method, to improve final-state measurement including isotopic identification, and to extract global characteristics of the fragmenting system like its volume and energy. In this context, HBT interferometry of charged and neutral particles can be exploited to infer the space-time properties of the source and, through recently developed imaging techniques, its density profile. Coupling such measurements for selected events to other global analysis would be ideal. The search of new signatures of the phase transition like the bi-disaggregate-modal behaviour and scaling of order parameter fluctuations should be pursued. Such an ensemble of new information will open the possibility for a detailed metrology of the phase transition.

To apply correlation techniques, which have proved to be successful in disentangling various scenarios, high statistics data and accurate event characterisation are required. More theoretical investigations must be devoted to understanding correlation functions and in particular the shape of the uncorrelated background and the normalisation. To sign the spinodal decomposition and to learn about the properties of the EOS symmetry term, information can be gained by varying the isospin content of the system and by experimentally identifying the isotope content of the final state. Such a study will require a new generation of multi-detectors and the availability, for sufficiently long running periods, of unstable neutron and proton rich beams with energies well beyond the Coulomb barrier. This programme must be integrated in the physics programme of the planned new facilities for Radioactive Beams at high intensity.

5.4 Nuclear collisions at relativistic and ultra-relativistic energies: fixed target experiment

Fixed target experiments at relativistic energies explore the nuclear phase diagram in the region of temperatures $T \simeq$50-100 MeV and high baryon densities, $n \simeq 2 - 5\, n_0$, bringing the system close to the phase boundary of the quark-gluon plasma. With the ultra-relativistic energies attained in the SPS, the QCD phase diagram was explored at higher temperatures and smaller baryon densities. Most recently, the SPS has lowered its beam energy to explore the intermediate region of baryon density.

The motivation to study nuclear matter at high baryon density is three-fold: (1) to measure the nuclear EOS, (2) to study the in-medium properties of hadrons, and (3) to explore possible new phases of nuclear matter at ultrahigh density. For the presently existing facilities the emphasis was to study the EOS and in-medium properties of hadrons. In the following, we first outline the current status of knowledge regarding the EOS as obtained from collective observables and kaon production. Secondly, we discuss data for both hadronic and electromagnetic signatures obtained in recent years, which imply that hadron properties are modified in a dense medium. Finally, we speculate on how to study new phases of nuclear matter at low temperature and large baryon density with the future accelerator facility at GSI.

During the last five years of operation at SPS the various experiments have collected a wealth of results which provide an unprecedented maturity in the understanding of the dynamics of heavy-collisions in the regime of ultra-relativistic energies. The data exhibit many of the predicted signatures for a quark-gluon plasma. We first describe the latest important experimental findings and their interpretation and then discuss how the remaining open questions can be answered in future fixed-target experiments.

EOS from collective motion. A systematic analysis of the particle emission pattern allows conclusions to be drawn regarding the pressure created in the early phase of the collision. However, a direct extraction of the EOS from non-isotropic flow patterns is difficult, since momentum-dependent (vector) forces and shadowing effects in semi-central collisions also influence the flow pattern. The elliptic flow has emerged as the most direct signal for the pressure built up during the early phase of the collision. The complete three-dimensional emission pattern for protons and isotopes of light nuclei was analysed by the FOPI collaboration for a number of collision systems and energies. The EOS collaboration measured the excitation function for the elliptic flow of protons at mid-rapidity, extending the energy range from GSI/BEVALAC energies up to 10.7A GeV. The trend of the measured elliptic proton flow compared to the predictions of a BUU transport calculation (Figure 5.7) suggests a transition from a stiff to a soft EOS with a transition point at around 4A GeV. In contrast, the analysis of the FOPI and KaoS results is in agreement with a soft EOS at energies around 1A GeV. A conceptual problem in the interpretation of the data originates from the strong transverse momentum dependence of the flow signal (Figure 5.7). Different transverse momentum cutoffs and dispersions in the determination of the reaction plane are sources of systematic deviations for different experimental set-ups. Finally the use of very charge-asymmetric beams will shed lights on the poorly known contributions to the isovector channel at high baryon density, of interest for neutron-star structure. Data on the neutron flow will be particularly relevant.

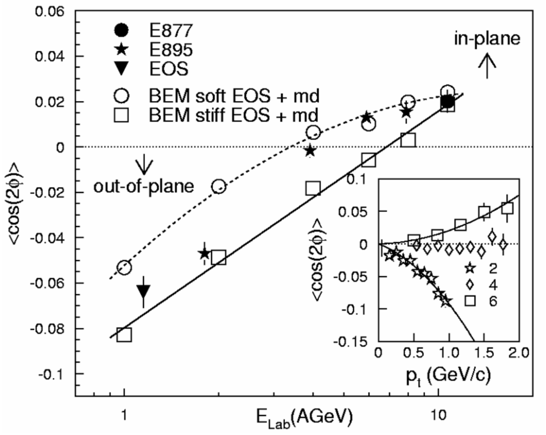

Figure 5.7: Excitation function of the proton elliptic flow at mid-rapidity measured at the AGS (full symbols). The open symbols represent results of transport calculation in the BUU framework. Two sets of parameters were used to study the effect of the stiffness of the EOS. Momentum-dependent interactions were used in both cases. In the insert, the momentum dependence of the flow signal is shown for three different bombarding energies (2, 4, and 6A GeV).

EOS from sub-threshold kaons production. Particle production at energies well below the free nucleon-nucleon production threshold is sensitive to the EOS of nuclear matter. At a given density, a lesser part of the energy is stored in compressional energy for a soft EOS compared to a hard EOS, and consequently more energy is available for particle production. In a recent theoretical interpretation of the KaoS results (low-Figure 5.8) a soft EOS is favoured. The K^+ multiplicity per participant nucleon in Au+Au collisions, normalised to the respective multiplicity in the comparatively light collision system C+C, decreases by about a factor of two as the beam energy rises from 800A MeV to 1.5A GeV. A transport calculation which includes momentum-dependent interactions as well as in-medium kaon potentials can reproduce the experimental results only if a soft EOS is assumed. It turned out that a repulsive in-medium potential of the K^+ meson is essential for a good overall description of the data.

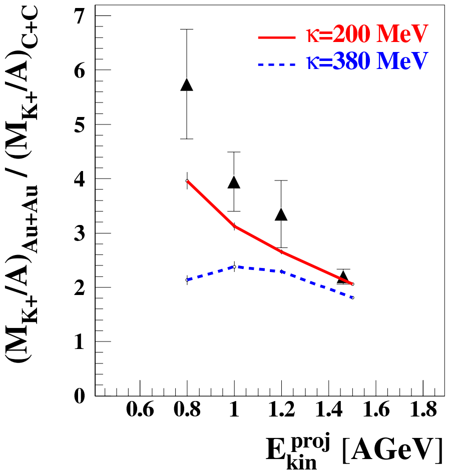

Figure 5.8: Excitation function of kaon production in Au+Au collisions near threshold. The yields are plotted relative to the Kaon production in C+C to emphasised the density effect. The BUU transport transport results are shown for two values of the compressibility.

Modification of hadrons in dense matter. Chiral symmetry is spontaneously broken in the QCD vacuum, which leads to a nonzero quark-antiquark condensate responsible for the large masses of the hadrons. It was conjectured that this chiral condensate should be substantially reduced as the baryon density and/or temperature increases. An observable consequence would be a modification of the hadron masses inside nuclei or in hot and dense nuclear matter. Unfortunately, the formation of hadrons is an aspect of non-perturbative (low-energy or long-wavelength) QCD, where explicit solutions are not available. Moreover, in a hot and dense environment, the hadronic spectral functions are modified due to interactions between various hadronic species making up the medium. A better understanding of hadron properties in a hot and dense environment is therefore one of the most important endeavours of nuclear physics today. Indications for in-medium modifications of hadronic properties have been found experimentally in two prominent cases.

In-medium kaon potential. Chiral perturbation-theory predicts attraction between K^- and nucleons and repulsion between $K^+$and nucleons. As a consequence, in the medium, the effective mass of the $K^-$is lowered and the K^+mass is increased. The potential becomes stronger with increasing density and consequently K^-can be produced at a lesser cost of energy as matter is compressed further. If this effect is realised in nature, it is predicted that the interior of neutron stars could develop a K^- condensate by electron absorption. The density at which the backward and forward reaction rates are balanced strongly depends on the effective mass of the kaons. The measured transverse emission pattern of K^+ mesons in the collision system Au+Au at $1A$ GeV presents a strong azimuthal anisotropy which contradicts the naive expectation that K^+ mesons are not influenced by the matter they traverse: K^+ are expected to have a long mean free-path, as they carry the anti-strange quark which cannot be exchanged with baryons. As can be inferred from transport calculations, this non-isotropic emission can only be reproduced if a repulsive K^+ potential is assumed - the K^+ are literally deflected by the dense region of the interaction zone. A final answer about the origin of this flow signal is expected from the respective data on K^- emission.

Modification of the in-medium vector meson spectral-function. Substantial evidence for a modification of light vector-meson properties in compressed and hot nuclear matter can be deduced from the spectral distribution of di-lepton pairs emitted in heavy-ion collisions. A huge excess of lepton pairs is found (data from CERES at the SPS) in the invariant mass region between contributions from pion Dalitz-decay and the location of the lightest vector-meson pole mass (between 200 and 700 MeV/c^2). The excess is established relative to contributions which arises from hadron decay after the collision zone has frozen out. It can be attributed to decays out of the interacting hadron gas, or even out of a deconfined phase. Microscopic simulations indicate that the most probable origin of these extra pairs is pion-pion annihilation. Vector dominance predicts that this annihilation proceeds through the ρ vector-meson. Simulations indicate that this process fills the region below the vector-meson pole mass only if the ρ-meson mass is substantially modified. The most exciting question arising is whether a partial restoration of chiral symmetry is responsible for a modification of the rho-meson spectral function. At the current level of data-quality a final decision on the origin of the enhancement cannot be made. It is important to note, however, that the surplus, quantified by the CERES collaboration as enhancement factor, rises, with increasing beam energy, from $2.9 \pm 0.3 \pm 0.6$ to $5.1 \pm 1.3 \pm 1.0$ (the errors refer to statistical and systematic uncertainties, respectively). As the baryon density at freeze out is smaller at higher beam energies, the enhancement might be linked to the presence of baryons. This is also supported by the result of the DLS collaboration, which found a large enhancement of electron pairs in the low-mass region for Ca+Ca and C+C at $1A$ GeV. The exploration of this energy regime will be followed up by the HADES experiment.

Nuclear Matter at High Net-Baryon Densities. The goal of future heavy-ion collision physics at relativistic energies is the precise mapping of the phase diagram in the region of high baryon density and moderate temperature. A number of fundamental physics questions is linked to this region of large baryon chemical potential: Is the observed modification of hadron properties in a dense nuclear medium due to the onset of deconfinement and/or chiral symmetry restoration? Is there a phase boundary between hadronic and deconfined matter or is a smooth cross-over realised in nature? Is there a critical point separating a cross-over transition from a first order phase-transition? Is cold, deconfined matter a colour superconductor? What is the effect of high isospin densities?

Our present knowledge about the phases of QCD relevant for nuclear collisions is summarised in Figure 5.9. The data points represent the *end points* of the evolution of hot and dense matter, at which inelastic collisions between the constituents cease. Their location indicates a universal freeze-out condition of constant baryon density. The picture illustrates the complementary approaches of present and future ultra-relativistic collider experiments and next-generation fixed-target experiments toward a better understanding of the microscopic properties of strongly interacting matter. Colliders will address the physics of hot, deconfined QCD matter. Experiments at moderate energies will concentrate on the properties of hadrons in compressed nuclear matter, using penetrating probes, and on mapping the QCD phase diagram to locate the critical point and the phase boundary at large densities.

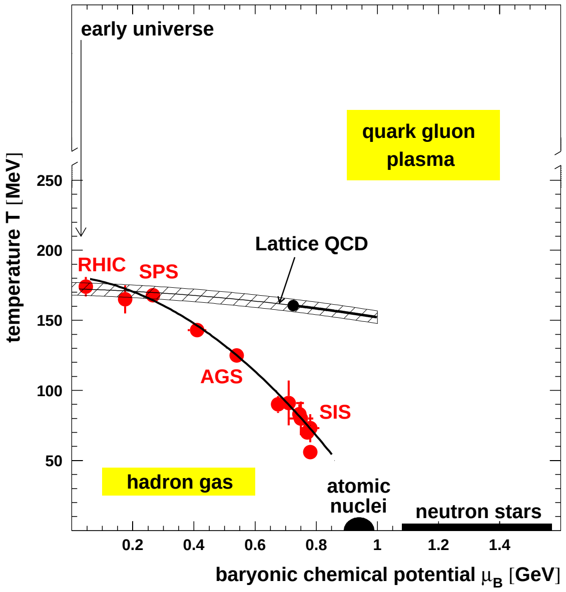

Figure 5.9: The phase diagram summarising the present understanding about the structure of nuclear matter at different densities and temperatures.

The region of very high net-baryon densities in the QCD phase diagram is, to a large extent, *Terra Incognita* both experimentally and theoretically. It can be reached in heavy-ion collisions at intermediate beam energies which create a fireball with moderate temperatures and baryon densities several times the density of ordinary nuclear matter. The experimental exploration of this high baryon-density regime is the main focus of one of the new GSI experiments, where nuclear matter will be created in collisions of very heavy-nuclei at energies from 2 to 30A GeV. The key observables are electromagnetic probes which provide undisturbed information from the interior of the fireball and, in particular, on the in-medium properties of hadrons. The experimental programme will be complemented by addressing charmed and hidden-charm mesons as well as multi-strange baryons, which have so far not been measured in the energy regime below 80A GeV.

Ultra-relativistic energies: Highlights from SPS. The new results obtained from the more differential measurements, performed the last five years, enabled a significant advance in our ability to substantiate the previously reached understanding of the dynamical evolution of heavy-ion collisions at ultra-relativistic energies. A common assessment of the data leads to the evidence that a new state of matter has been created, at energy densities which have never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter features many of the characteristics of the theoretically predicted quark-gluon plasma. In addition to the excess of low-mass dielectrons, already discussed earlier, several characteristic features were established.

Dynamics of the collision. The relative abundance of hadrons in the final state of the collision, their momentum distribution and their space-time distribution, are reminiscent of the early dense stage of the collision and of its dynamical evolution. The combined analysis of these observables measured by the SPS experiments indicate that at freeze-out the fireball has a temperature of 100-120 MeV. It expands explosively with velocities exceeding half the speed of light which is an indication for the existence of strong pressure in the early stage of the collision. Flow measurements further indicate that the pressure builds up quickly as a result of rescattering in the early collision stage. The statistical analysis of the measured relative abundance of hadrons concludes that hadrons are produced in a state of chemical equilibrium at a temperature of about 170 MeV, i.e. very early in the collision, close to the predicted critical temperature (Figure 5.9) at which hadrons dissolve into quarks and gluons. Hadron yields thus reflect quite closely the conditions at hadronisation.

Strangeness enhancement. Enhanced strange-hadron production, with the enhancement being larger the larger the strangeness, has been observed (NA49, NA57 experiments) in heavy-ion collision relative to normalised proton-proton collisions. The strangeness-production process, because of the early frozen chemical composition, can only act before or during hadronisation and is thus favoured by high gluon densities and reduced strange-quark mass in a chiral symmetric quark-gluon plasma.

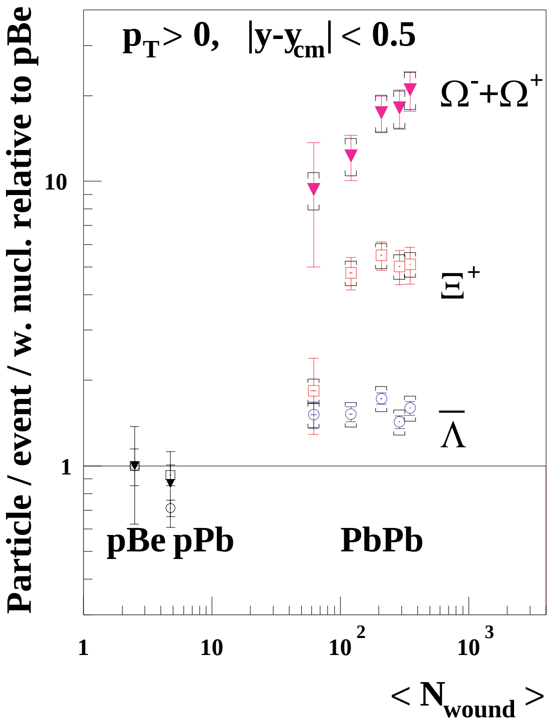

Figure 5.10: Hyperon yields per wounded nucleon in Pb+Pb relative to p+Be at 158A GeV as a function of the number of wounded nucleons. Black bars represent systematic errors.

Charmonium suppression. The heavy $c\bar{c}$ pair which, at the modest SPS energy, can only be created in a hard parton-collision during the initial phase of a nucleus-nucleus reaction serves as a probe of the surrounding matter at high energy-density. The evolution of an initial pair toward its final J/ψ or $\psi\prime$ hadronic state could be blocked if it is embedded in a state of deconfined quarks and gluons. In such a medium, Debye screening renders colour interactions short-ranged, thus breaking up the co-travelling $c\bar{c}$ pairs (like any other hadronic bound states), to end up in open charm mesons. A suppression of J/ψ and $\psi\prime$ events in central nuclear collisions was thus expected during a dynamical evolution proceeding via a deconfinement phase. An anomalous suppression of J/ψ has indeed been observed (NA50 experiment) in central Pb-Pb collisions at 158 GeV/c (Figure 5.11) The suppression pattern, showing a departure from normal absorption at $E_T = 40$ GeV and no saturation at high E_T, is currently interpreted in the QGP scenario as sequential suppression of two $c\bar{c}$ states, first the

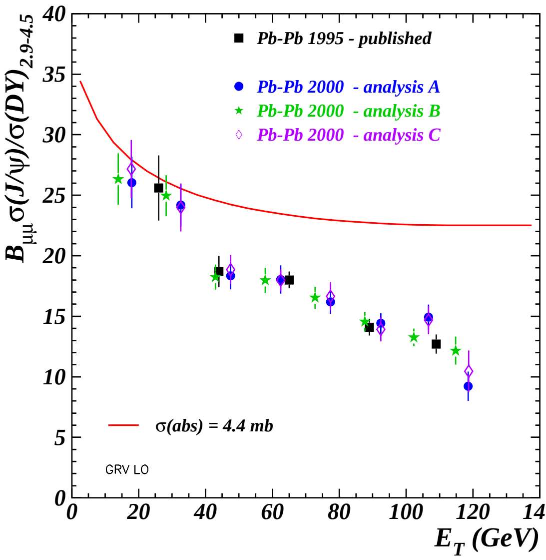

Figure 5.11: Ratio of the J/ψ production measured in the $\mu^+\mu^-$ channel normalised to the Drell-Yan production as a function of collision centrality, measured by the total transverse energy. The solid line represents the normal absorption reference measured with high statistics in proton induced and S-U collisions and corresponding to an absorption cross-section of $\sigma_{abs} = 4.4$ mb. The early (1996) peripheral data polluted by the admixture of Pb-Air interactions have been corrected by new data (2000) taken with the target in vacuum.

χ_c and then the J/ψ. However some questions regarding e.g. E_T fluctuations in central collisions are still unanswered and the identification of χ_c and J/ψ in the suppression pattern must be considered only tentative. In addition a few of the non-QGP models cannot yet be ruled out by SPS data.

The ideal normalisation for the study of charmonium suppression would clearly be the yield of charmed mesons. Until now, no direct measurement of open-charm production has been performed at SPS energies. From the yield of di-muons measured by NA50 in the intermediate-mass region between the ϕ and the J/ψ mass, one would derive a considerable increase in charm production as compared to the extrapolation from p-A data. Still the existing data are also

compatible with an increased yield of virtual photons. To solve this problem and finally provide a direct measurement of charmed mesons in ultra-relativistic nuclear collisions, a dedicated experiment, NA60, has been approved at the SPS.

Outlook. By now there is ample evidence for a (most likely, smooth) change of hadronic properties inside nuclear matter as the density and/or temperature of the surrounding matter is varied. A consistent description of the microscopic properties of nuclear matter is, however, still lacking. Microscopic transport codes play a key role in the interpretation of experimental results. In most cases they represent the only tools to link theoretical predictions to experimental observables and to achieve a comprehensive picture of heavy-ion collisions. Statistical models are rather successful in describing the bulk observables even in energy regimes and for collision systems where true thermal equilibrium is most likely not achieved. To reconcile these diverse pictures, the following steps seem to be indispensable: i) Conduct further experiments to complete a full three dimensional mapping of particle emissions at low energies (FOPI collaboration); ii) Include off-shell transport and/or three-body forces in microscopic transport codes; iii) Systematically measure excitations functions of in-medium properties using penetrating probes; iv) Measure specific elementary cross section to further constrain effective field theories; v) Systematic study of isospin effects on collective flows and particle production.

The spectra of penetrating probes, such as di-leptons and photons, yield information about the early stages of the collision. They are therefore essential for the study of nuclear matter at high net baryon-density. The challenge of future experiments is to compile this information in unprecedented detail. This comprises high-resolution di-lepton spectra as well as the measurement of charm production with high statistics. The complexity of the reaction requires systematic investigations of double-differential cross sections as a function of beam energy and system size. These efforts have to be flanked by a common endeavour to develop further transport theories incorporating off-shell transport and many-body interactions. The proposed future accelerator facility at GSI will provide ideal conditions for a second-generation multi-purpose experiment being addressed to the physics of highly compressed QCD matter: The high availability of an intense heavy-ion beam up to energies of $30A$ GeV (lower SPS energies) would allow high-rate measurements; The maximum energy reaches above the production threshold for charm, lepton pair spectroscopy could thus be complemented by the detection of charmonium and mesons with open charm. We fully support the strategy outlined in the Compressed Baryonic Matter (CBM) proposal to combine HADES with a new set-up to form a universal detection system covering a beam energy region from 2 to $30A$ GeV well suited to create and study highly compressed nuclear matter.

5.5 Nuclear collisions at collider energies

Nucleus-nucleus collisions at collider energies explore the properties of dense matter close to vanishing baryochemical potential. At the high centre-of-mass energies of $\sqrt{s_{NN}} < 200$ GeV at RHIC and $\sqrt{s_{NN}} = 5.5$ TeV at LHC, these collisions yield a rich variety of so-called *hard* non-equilibrating probes which are produced in the first fm/c of the collision. Beyond merely establishing signatures for its existence, the medium-dependence of these hard probes provides an unparallelled possibility for a detailed quantitative study of the transient partonic state. To make full use of these possibilities requires sufficient integrated luminosity at collider energies to analyse very rare hard probes as e.g. bottomonium production or Z-production in nucleus-nucleus collisions. Moreover, for the interpretation of these observables one needs to calibrate the medium-dependence of hard probes with respect to their unmodified behaviour. This requires for benchmark measurements in $p-p$ and $p-A$collisions at comparable $\sqrt{s_{NN}}$, and systematic scans in energy $\sqrt{s_{NN}}$ and nuclear size A.

Highlights from RHIC. In June 2000, ultra-relativistic heavy-ion physics entered the collider era when Brookhaven National Laboratory's (BNL) Relativistic Heavy Ion Collider (RHIC) reported the first collisions between gold nuclei at centre-of-mass energies of $\sqrt{s_{NN}} = 130$ GeV. Since 2001, a comprehensive set of data is collected in collisions at the design luminosity and energy, $\sqrt{s_{NN}} = 200$ GeV (a factor of ten increase over the maximum energy attained previously at CERN-SPS) including reference measurements in $p-p$ and $d-A$ collisions. Future Au-Au runs plan to accumulate sufficient luminosity for the detailed study of leptonic and rare hadronic observables such as the spectra of dileptons, direct photons and J/ψ.

The data obtained in central Au-Au collisions indicate that an almost baryon-free and thermalised medium is formed with energy densities exceeding the critical energy-density predicted for the QCD phase transition.

Particle multiplicities. The maximum energy-density is deduced from charged-particle density and transverse-energy density measured in the central rapidity region. Figure 5.12 shows the charged-particle rapidity density measured over a broad center-of-mass energy. When compared to the particle density measured in $p-p$ collisions, a sizable medium effect is revealed in $A-A$ collisions. This observation is an indication of the occurrence of multiple scatterings which thermalised the medium. The density reached at RHIC is about a factor two higher than the one measured at SPS. Yet, it is well below extrapolations performed from SPS measurements, reflecting that there exists no first-principle calculation of this observable. Indeed, extrapolation from the RHIC to LHC energies, i.e. over more than one order of magnitude, can only be indicative.

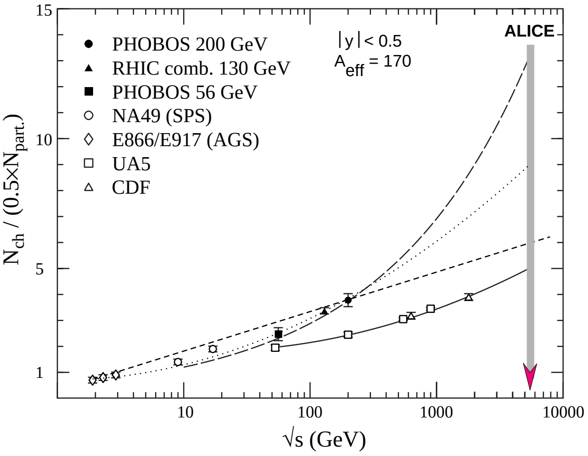

Figure 5.12: Charged-particles rapidity density per participant pair as a function of centre of mass energy for $A-A$ and $p-p$ collisions. Lines show different parametrization of the energy dependence, being logarithmic (dashed line), square logarithmic (solid and dotted lines) or power law (long-dashed line). The arrow indicates the nominal LHC energy.

Hadrochemical Composition. The baryon to anti-baryon ratio measured at RHIC is close to unity, a factor more than ten times larger than the one measured at CERN-SPS. Fits of a thermal model of statistical hadroproduction to many measured particle yields and baryon-to-anti-baryon ratios, lead to the conclusion that the chemical freeze-out (Figure 5.9) takes place at a temperature $T \approx 175$ MeV and at a baryochemical potential $\mu_B \approx 30$ MeV, i.e. at the phase boundary between confined and deconfined matter. This interpretation of the data indicates that the medium formed early in the heavy-ion collisions is close to the QCD vacuum heated at temperatures well beyond the critical temperature. However, it should be emphasised that such an analysis does not provide a direct test of thermalisation, since the model relies only on the assumption that dynamical constraints are negligible and that multi-particle phase space is filled uniformly according to the principle of maximum entropy.

Collectivity. Elliptic flow, which describes the azimuthal asymmetry of particle production in semi-central collisions, is sensitive to the degree of thermalisation achieved in the system. It builds up through re-scattering in the evolving system which converts the spatial anisotropy in the entrance channel into momentum anisotropy. The rapid expansion of the hot system destroys the original anisotropy and quenches the build up of the momentum anisotropy. Therefore elliptic flow is particularly sensitive to the early stage of the collision. The surprisingly large elliptic flow measured at RHIC saturates the predictions of the hydrodynamical model for a wide range of momenta, below 2 GeV/c, and particle types. This behaviour is an indication that a high degree of local thermalisation is reached at early times followed by a collective hydrodynamic expansion.

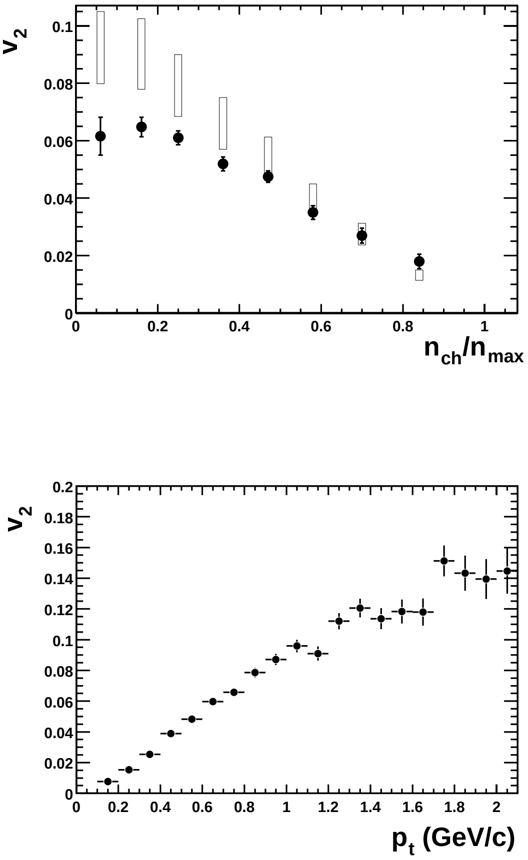

Figure 5.13: Top: Elliptic flow as a function of centrality. The open rectangle show a range of values expected in the hydrodynamic limit. Bottom: Elliptic flow as a function of transverse momentum for minimum bias events. STAR data.

Hard Probes. At RHIC, thanks to the high centre-of-mass energy only attainable with colliders, a new probe has become available: high transverse momentum hadrons. These hadrons are created through the fragmentation into jets of partons scattered, through hard processes, in the initial stage of the heavy-ion collision. Such fast moving partons are a particularly interesting probe of hot nuclear matter: they are expected to have larger energy loss in a medium of deconfined colour charges than in normal nuclear matter. This energy loss would in turn be visible as a reduced yield (a quenching) of high momentum hadrons in central $A-A$ collisions. The effect was indeed observed (Figure 5.14) at RHIC. This observation indicates substantial energy loss of the final state partons or their hadronic fragments in the medium generated by high energy nuclear collisions.

The production of jets has been further demonstrated in angular correlations of high transverse-momentum hadrons through the observation of enhanced correlations at $\Delta\phi \sim 0$ and $\Delta\phi \sim \pi$. The strong reduction of the back-to-back correlations observed in the most central heavy-ion collisions indicates significant interaction of hard scattered partons or their fragmentation products as they traverse the matter created in the collisions.

The future at the LHC. The LHC is now scheduled to start operation in 2007. The acceleration of nuclear beams is part of the ini-

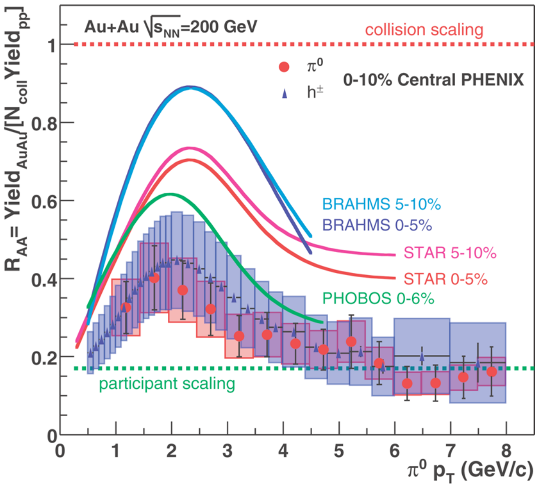

Figure 5.14: Evolution with hadrons transverse momentum of the nuclear modification factor, defined as the ratio of the hadron yields in nucleus-nucleus and the yield in nucleon-nucleon interactions scaled by the equivalent number of binary nucleon-nucleon collisions which accounts for the collision geometry.

tial programme: a pilot run is foreseen for the first LHC year, and a run of typically 10^6 seconds of useful beam time is planned once a year. The LHC will provide Pb ions at a centre-of-mass energy of 5.5 TeV per nucleon, which represents a jump of a factor 30 with respect to the RHIC energy. It will therefore lead into a radically new energy region, previously reached only in the interactions of the highest energy cosmic rays. The construction of the experiments is advancing rapidly, in order to be ready with the apparatus fully commissioned at the start of the beams. Four experiments will operate at the LHC. Of these, one, ALICE, will be dedicated to Heavy Ions, another one, CMS, is dedicated primarily to pp but features a well defined HI programme, a third, ATLAS, has expressed an interest in running with Heavy Ions. Being the only dedicated experiment for the study of nuclear collisions at the LHC, ALICE is essentially a *Heavy Ion Programme* which covers, in one experiment, the full range of relevant observables in Heavy Ion collisions. CMS, on the other hand, is optimised for the study of high transverse momentum processes, and will therefore focus on these observables only. The experimental programme with Heavy Ions at the LHC foresees runs with Pb-Pb, proton-nucleus, and lighter ions (probably Ar-Ar). The LHC will provide every year a few weeks of running with nuclear beams, as the SPS did in the past. Heavy Ion collisions at the LHC will provide a qualitatively new environment, with ideal conditions for the study of the QGP. The higher energy will improve all parameters relevant to the formation of the QGP: energy density, size and lifetime of the system will all improve by large factors, typically an order of magnitude. The initial temperatures will largely exceed the calculated critical temperature for QGP formation, therefore allowing the study of QGP in its asymptotic ideal gas form. In the central region the net baryon number density will essentially vanish, further improving relative to RHIC the ease of comparison with lattice QCD calculations and the closeness to the conditions of the primordial universe.

Even more important, though, will be the possibility to exploit a wider set of relevant observables as compared to previous accelerators, thus substantially enhancing the understanding of the properties of the system. First of all, the higher energy and high luminosity will improve access to the hard probes sensitive to the earliest stages of the medium. The study of jet production and therefore of the propagation of fast partons will find at the LHC its ideal environment, allowing the study of the jet fragmentation functions up to well over 100 GeV/c of Jet p_T. The excellent particle identification capability and good coverage in transverse momentum of ALICE will allow the detailed study of the fragmentation functions. The study of the jet recoiling against a photon will enable the fast parton energy loss to be measured. The study of the heavy quark potential will benefit from the possibility to measure both the charmonium and bottomonium families, which provide a wide range of radii and binding energies, and of measuring in the same experiment the production of open charm and beauty mesons, and even of the contribution of B meson decays to the J/ψ yield. The temperature of the medium should be high enough to allow a precise measurement of the direct photon spectrum, which would be a thermometer of the early phase of the system.

In addition to the new insight provided by the hard probes, collisions at the LHC will feature very high multiplicities, allowing the measurement of a large number of observables on an event-by-event basis: impact parameter, multiplicity, particle composition and spectra and HBT parameters of the system. Therefore single event analysis, and in particular the study of non-statistical fluctuations associated to critical phenomena, can be effectively peformed at the LHC.

To address in a comprehensive way the full set of relevant observables, ALICE has expanded along the years the scope of its apparatus. To the original central detector, providing excellent tracking and PID for hadrons and limited lepton identification, first a forward muon arm, than a barrel TRD have been added, allowing a full spectrum of lepton measurements. A High Level Trigger is being developed to enhance the sensitivity to low-cross section processes, and a large-area Electromagnetic Calorimeter is being proposed. The value of the magnetic field in the central magnet has also been increased for the bulk of the running time to 0.5 T. This change, combined with the additional lever arm provided by the TRD, allows ALICE to measure momenta with good precision up to the highest values of transverse momentum relevant for Jet Physics in Pb-Pb at the LHC, given the available luminosity: close to 10% at 100 GeV/c. Contextually, the performance of the detector has been reassessed and a specific Physics Performance Report is in preparation.

At the moment, all of the ALICE sub-detectors have successfully completed the R&D phase, reaching performances often exceeding the design goals. The technological developments carried on during this development phase have been formidable, and are already finding numerous applications in other Nuclear Physics experiments but also in different fields of applied physics. The present challenge for the collaboration is the construction and commissioning of the apparatus. While the individual sub-detectors are entering the production phase, an enormous effort is demanded from the participating institutions to carry on the construction and commissioning effort. In order to reach the 2007 date with a detector fully operational and debugged at the system level, the relentless commitment of both the experimenters and their institutions will be needed throughout the next five years. Contextually, the software and more generally computing tools necessary to analyse the enormous data volumes produced at the LHC are being developed, and will require a dedicated effort in the coming years.

Computing requirements. The evolution of the particular field in nuclear physics which studies the phases of nuclear matter requires large amounts of computing resources and will, within the next five years, require unprecedented large amounts. The type of resources are different if the theoretical needs or the experimental needs are considered. However, with the future deployment of GRID middle-ware, which will enable to federate many of the resources available to the discipline around the world, the required needs could be satisfied, but only with additional national and regional computer fabrics.

The increasing sophistication introduced in the modelling of heavy-ion collisions at any energy (stochastic transport models, collision simulations starting from first principle) and the application to the real-world of QCD calculations (lattice QCD with finite quark masses, finite baryonic number and finite temperature) are increasingly CPU time greedy but produce only small amounts of data. Large farms, super calculators, massively parallel calculators are typically the type of computing resources the applications in theoretical nuclear physics needs access to.

The amount of data which will be collected by the ALICE experiment requires, on the other hand, storage capacities which will exceed by orders of magnitude the largest particle-physics experiment (BaBar) presently in operation (from Tera bytes to Peta bytes). The increase in CPU needs is comparable both for data processing and the production of Monte-Carlo data. These needs can only be met by federating many of the resources available throughout the world for the heavy-ion physics programme.

We recommend strongly that NuPECC supports the existing programme and new initiatives aiming at the deployment of GRID kind of projects. Although the demands of theory and experiment are not contradictory and could in principle be satisfied using the same approach, we recommend new initiatives toward dedicated computing facilities for theory computation.

Outlook. Heavy-ion collisions at the LHC will be *the* future of the ultra-relativistic heavy-ion programme in Europe. It is of utmost importance that the significant investment made at LHC will be exploited fully and without any sacrifice. The highest future priority is, therefore, the completion of the ALICE detector and the exploration of the heavy-ion physics capabilities of the CMS and possibly ATLAS detectors. This requires the full commitment of the community and its resources, especially in the critical years of construction.

Heavy-ion physics at collider energies addresses a combination of luminosity-dominated and systematic-dominated questions. It is clearly indispensable for the success of the LHC heavy-ion programme that ion beams of sufficient integrated luminosity and sufficient variety are provided. We strongly urge, therefore, taking all necessary steps for delivering Pb ion beams in year one of LHC running, and to accumulate $\approx 1\text{nb}^{-1}$ of Pb+Pb data (equivalent to one month running at design luminosity) at the earliest possible time to establish e.g. jet quenching observables out to $E_T \simeq 200$ GeV. The study of rare processes such as the production of bottomonium states will require significantly higher integrated luminosity during the subsequent years. Moreover, we consider it compulsory to establish bench-mark results for comparison by studying $p-p$ and $p-A$ collisions within the first four years of LHC running. For a full systematic study, we further emphasise the need for several lighter ion beams.

The LHC heavy-ion programme has an unparallelled opportunity to go qualitatively beyond the physics done at RHIC in particular by studying hard processes embedded in matter at extremely high energy-densities. We strongly support, therefore detector upgrades which improve the physics capabilities of ALICE at high transverse momentum. This includes in particular the completion of the Transition Radiation Detector, the addition of an electromagnetic calorimeter for jet measurements, and the development of new technologies and analysis methods for extending high-momentum particle-identification beyond $p_T \sim 5$ GeV.

The Relativistic Heavy Ion Collider (RHIC) in Brookhaven has produced exciting results within the first two years of running. A further European participation in RHIC and the participation in a possible RHIC upgrade would be reciprocated by a comparable participation of US groups in the LHC heavy-ion programme.

5.6 General outlook

The LHC heavy-ion programme will become a major endeavour of nuclear physics and place Europe in a world leadership role in nuclear science. Full support must be given to ensure the readiness of the machine to deliver heavy-ion beams in the first year of operation, and to guarantee the timely completion of the ALICE experiment, presently in its construction phase.

We strongly support the construction of the future high luminosity synchroton facility at GSI and the full exploitation of its high-energy option. We recommend a vigorous R&D aiming at the construction of a high rate detector system dedicated to the exploration of compressed baryonic matter.

For the Fermi-energy domain we recommend that the community has continuous access to the radioactive-beam facilities with improved detection systems to prepare an unique scientific programme at the future EURISOL and GSI facilities.

Theoretical support is crucial for progress in nuclear physics. Additional funding for nuclear theory at the national and European levels has to accompany the significant investment into large experimental programmes. Career perspectives must be given to young researchers.

The study of the phase diagram of nuclear matter will require unprecedented computing resources to cope with the huge amount of data expected and with the complexity of the nuclear many-body problem. We recommend that computing infrastructure is adequately supported.

We recommend that sustained support for facility operations and limited detector upgrades is provided to ensure the continuous exploitation of the existing facilities at all energies.

6. Nuclear Structure

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6.1 Introduction: why study the structure of an atomic nucleus?

At the heart of all atoms that make up our universe lies the atomic nucleus: a minute system with a well-defined number of protons (Z) and neutrons (N). Although of negligible dimension in terms of size - the radii of the atom and its nucleus differ by four to five orders of magnitude - the atomic nucleus accounts for over 99% of the mass of the atom and of all visible mass in the universe. Understanding its properties, which is the final goal of nuclear-structure research, is therefore central to the global fundamental research endeavour in which our society is involved.

The atomic nucleus is a unique laboratory for studying different fundamental physics phenomena. It is made of a finite number of strongly interacting fermions and its properties are governed by the interplay between the electromagnetic, weak and strong interactions. As such the nucleus exhibits several features like few- and many-body phenomena in their broadest sense and the way the fundamental interactions manifest themselves inside the atomic nucleus. Microscopic as well as mesoscopic features driven by effective two-body and eventually three-body forces, that depend on distance, angular momentum and density, and by effective degrees of freedom can be studied in this quantal laboratory. The experimental determination of the properties of the atomic nucleus in addition to the theoretical modeling of the system have major implications for the understanding of other quantal systems such as Bose-Einstein condensates, metallic clusters and high-T_c superconductors. Few-body models widely used in atomic and molecular physics, various astrophysics questions like nucleosynthesis scenarios, fundamental interaction studies and the standard model, as well as numerous applications all benefit from the study of nuclear structure.

In the past the nucleus has provided us with surprises and challenges every time new and ingenious detection techniques and more advanced accelerators were introduced along with the development of new theoretical models. Nevertheless, most of our present-day understanding of nuclear structure and of the way protons and neutrons “stick” together under the influence of the strong nucleon-nucleon force derives from the study of a rather small “patch” in the (Z,N) plane of atomic nuclei at quite low values of excitation energy and rotation (or spin), and from the study of a limited number of open decay channels, be it natural decay or induced via nuclear reactions. However, our field now stands on the verge of a new era of radioactive beam physics and innovative experimental techniques. Radioactive ion beams (RIB) and the related developments in instrumentation will lead us into the unknown territory of the nuclear chart allowing unprecedented studies.

The strategy as how to learn more about how the nucleons are organised inside the nucleus and to discover a number of simple modes of motion has been based on two general approaches: (i) the system can be taken apart into its constituents (studying the ways in which unstable nuclei decay by emitting particles or photons on their way back to stability) or (ii) use can be made of external fields (electromagnetic, weak and strong probes) to observe how the system responds. These two methods have revealed some of the essential degrees of freedom active inside the nucleus by investigating the various eigen-frequencies with which the nuclear many-body system resonates. This general research strategy will not be altered, however, the availability of new beams and instrumentation, as well as innovative theoretical developments will deepen our understanding of a number of long-standing issues (see box "Long-Standing Questions") while at the same time we expect to encounter new surprises and challenges.

Our current understanding is briefly reviewed from a theoretical point of view, after which some experimental achievements from the last five years are presented. The current status and future developments of the instrumentation and facilities then lead finally to the conclusions and outlook.

6.2 The current understanding of the atomic nucleus

"From QCD over ab-initio calculations to local and global models".

Our knowledge of nuclear-structure is mainly based on the properties of nuclei in the neighbourhood of the line of β-stability and their properties are reasonably well described by various models. Recent developments starting from the bare nucleon-nucleon interaction and based on first principles result in a successful description of light nuclei (A $\leq$ 10), including those with extreme proton-to-neutron ratios. However, a number of the basic ingredients are still not fully understood.

During the last decade, significant progress has been made both experimentally and theoretically. The field of RIB has allowed us to move away from the line of stability and go from a one-dimensional picture (mainly A as parameter) to a two-dimensional picture (with N and Z as parameters). First results indicate that extrapolations of our current understanding based on smoothly varying proton and neutron numbers, angular momentum or excitation energy fail. This failure is of a fundamental nature due to the unique character of the problem and not simply due to the use of a wrong set of parameters or an oversimplified approximation. The nucleus is a finite, many-body system whose constituents interact via a strong interaction that cannot be treated in a perturbative way and where in general, the small number of nucleons in the nuclei does not allow the use of statistical methods available in other fields. Thus, the atomic nucleus is one of the richest but at the same time one of the most challenging quantal systems in nature.

Despite these challenges, however, concerted research efforts over recent years have identified new routes that might lead to a more complete and accurate description of the atomic nucleus.

Long-Standing Questions

Atomic nuclei are quantum systems with a finite number of strongly interacting particles that exhibit different degrees of freedom manifesting themselves in many ways. A rich spectrum of microscopic and mesoscopic phenomena, including few-body and many-body effects and ranging from QCD "free-nucleon" interactions to "in-medium" effective interactions, can be studied. Nuclear-structure research aims at understanding and predicting the properties of the atomic nucleus, to learn through its modelling about the underlying physics concepts and to extract the simple basic ingredients. The crucial, often long-standing, questions are:

- What are the limits for existence of nuclei? Where are the proton and neutron drip lines situated? Where does Mendeleyev's table end?
- How does the nuclear force depend on varying proton-to-neutron ratios?
- How to explain collective phenomena from individual motion?
- How are complex nuclei built from their basic constituents?

The "Basic Truths" Revisited

What we have learned over the last decade of research on exotic nuclei forces us to revise some of our "basic truths". These were deduced from intensive studies of stable nuclei, but it has become clear that stable isotopes do not exhibit all features.

- *Nuclear radii don't go as* $A^{1/3}$.
  For all stable isotopes the density in the atomic nucleus as well as the diffuseness of the surface are nearly constant. Explorations into the far-unstable regions of the nuclear chart have convincingly shown that the diffuseness, and thus the radii of the atomic nuclei, vary strongly.
- *Magic Z and N numbers depend on N and Z, respectively.*
  Shell gaps seem to shrink or disappear, and new ones appear when leaving the valley of stability. Also, experimental evidence for new deformed magic numbers is now available.
- *Many more bound nuclei exist than anticipated.*
  The neutron drip line is much further out than anticipated twenty years ago. The importance of nucleon correlations and clustering that create more binding for the nuclear system has been underestimated.

They have also forced us to review what we considered to be of as our basic understanding of nuclear structure (see box "The "Basic Truths" Revisited"). One of the most fruitful avenues for elucidating specific aspects of the nuclear interaction and dynamics has proven to be the study of nuclei under extreme conditions be it isospin, proton-to-neutron ratio, excitation energy or angular momentum. This will enhance or suppress certain components of the interaction. Experimental studies of these extremes will not only provide firm guidance for the development of theoretical models, but they will certainly uncover exciting new phenomena.

It is of vital importance to our complete understanding of nucleonic matter and hence of the fundamental laws and interactions of nature that we explore the limits of nuclear stability and invest in the new experimental facilities (accelerators, detectors, data acquisition, computing power. . .) and new theoretical developments necessary to achieve this aim. The ultimate goal of nuclear-structure research is to construct a unified theory of nuclear matter and finite nuclei, from strongly bound stable nuclei to weakly bound highly unstable ones, from the very light few-body systems to super-heavy nuclei.

6.2.1 The nucleon-nucleon force

The nucleus is a typical example of a self-bound system. The case of atoms, in which the electronic motion is largely dictated by their Coulomb interaction with the atomic nucleus contrasts with atomic nuclei where the weak, electromagnetic, and strong forces are at play. This results in complexities and regular structures. Today we adopt QCD as "the theory" of the strong force. It has been conjectured that - much like molecules interact through an effective force resulting from the fundamental electromagnetic interaction between their constituent electrons - nucleons interact by an effective force whose origin is in the QCD interaction between their quark-gluon constituents. More details on this topic are presented in the chapter on QCD.

An improved understanding of the effective nuclear interaction is a major goal of contemporary theory of systems of strongly interacting hadrons. The effective nucleon-nucleon interaction can, in principle, be derived from the bare nucleon-nucleon force. Compared to the free two-body nucleon-nucleon interaction, which can be fairly well determined from scattering experiments, the effective interaction must absorb the following four physical effects:

- Presence of a short-range repulsion which requires a complete non-perturbative treatment of the two-particle problem.
- Many-body interactions

- Modification of the interaction by the medium of nucleons in which it occurs.
- Reduction of the available phase space in free nucleon-nucleon scattering when coming to the bound many-body states because of Pauli-blocking.

Based on the symmetry-breaking patterns of QCD at the low-energy and momentum scales relevant to nuclear physics, new conceptual frameworks are being developed using the effective field theory approach and advanced methods such as renormalisation group techniques. Establishing the connection between such advanced theoretical approaches and the vast amount of quantitative phenomenological knowledge that has been gained about the nuclear many-body problem, is an important task for the near future.

In many applications one uses phenomenological effective interactions fitted to experimental data. Such approaches are very successful, showing that the concept of an effective interaction applies considerably well to atomic nuclei. In particular, one may use the effective interaction either in microscopic mean-field approximations or in shell-model diagonalisations (see section 6.2.4. The strong links, which exist at present between experiment and the approaches using effective interactions, call for an extension to the study of nuclei far from stability as this provides in fact one way of establishing the properties of the effective interactions. Moreover, the matter at the nuclear surface characterised by strong density gradients becomes more diffuse in drip-line systems where clusterisation and specific correlation effects might show up (see Figure 6.1) where pairing in infinite symmetric nuclear matter is discussed).

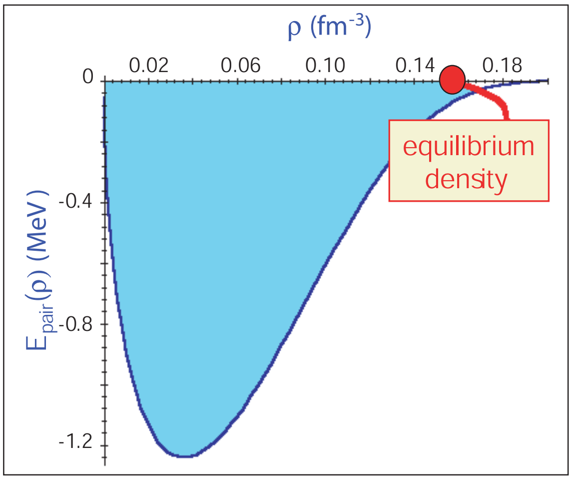


Figure 6.1: The pairing-energy density per nucleon, obtained by solving the momentum-dependent BCS gap equations self-consistently with the singlet-even part of the free-space Bonn NN-potential, is shown as a function of the density of nuclear matter. The location of the maximum at about 1/4 of the saturation density shows that pairing is a low-density phenomenon and that it becomes increasingly important in weakly bound halo and skin nuclei.

6.2.2 Nuclear reactions

The past decade has witnessed a resurgence of interest in modelling direct nuclear reactions which has been almost entirely due to the advent of RIB, and in particular to the discovery of halo nuclei. Many standard theoretical tools used in reaction models have been found to be unreliable for the description of reactions involving light exotic nuclei produced in RIB. An early example of this was the realisation that even for a simple quantity such as the matter radius of halo nuclei the few-body degrees of freedom of such quantum systems have to be taken into account. In addition to this, approaches such as time-dependent techniques, both perturbative and non-perturbative have been further developed. An important issue regarding reactions is the interplay between the nuclear and Coulomb interactions and how these can be treated consistently within the same model.

In general, nuclear-structure information in many reaction models enters in the form of “overlap functions”. Therefore, how these quantities are calculated depends on the approximations made along the way in reducing the many-body problem to a more manageable one(-or few)-body one. Theorists are apprehensive about issues such as energy dependence and non-locality that appear in the equations as a result of this reduction.

Transfer reactions, like for example pair-transfer reactions, fusion reactions and Coulomb

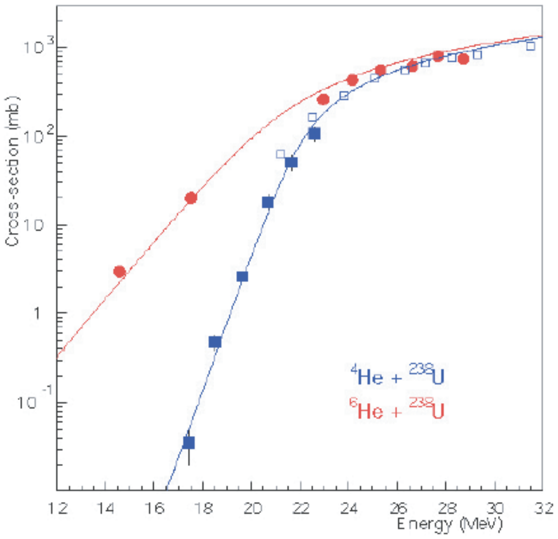


Figure 6.2: Absolute fusion-fission cross sections as a function of bombarding energy for ^{4}He (full and empty blue squares) and for the light halo nucleus ^{6}He (red dots) on ^{238}U are shown. The strong enhancement of the ^{6}He cross section below the Coulomb barrier is believed to be due to a neutral transfer reaction.

excitation will be vital for studying the structure of exotic nuclei (see Figure 6.2 and box "First Results from SPIRAL and REX-ISOLDE"). Unlike high energy knock-out reactions, that have proven to be an excellent probe of single-particle components in the nuclear wave function, low energy transfer reactions often involve complicated reaction mechanisms in which coupling to intermediate channels must be incorporated into the calculations. It will therefore be a challenge to extract reliable and detailed structure information. Also, results of experiments with polarised energetic beams of radioactive nuclei will be of considerable interest in the future and several theoretical reaction models are being developed in anticipation.

Electromagnetic probes of exotic light nuclei are expected to be complementary to those fragmentation reactions involving the strong interaction. New experimental facilities planned for electron-radioactive beam colliders at RIKEN in Japan and GSI in Germany, will provide novel ways of studying the structure of light exotic nuclei through elastic and inelastic electron scattering, knockout and electroproduction reactions. Theoretical support in this area will therefore be vital.

From a purely theoretical point of view, a major challenge is to incorporate into reaction models sufficiently detailed microscopic information about the internal structure of the interacting nuclei. For example, applying the cluster decomposition of the many-body wave function describing light exotic nuclei in few-body reaction models, in which antisymmetrisation can be fully taken into account, will be of great interest.

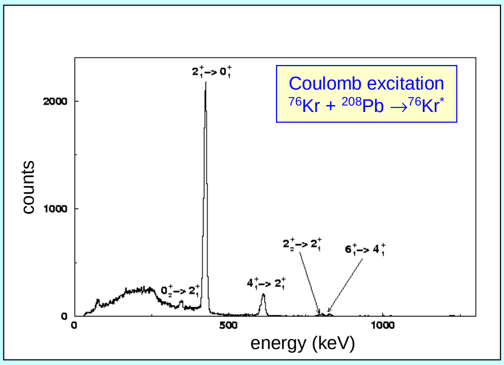
6.2.3 Few-nucleon systems

In studying light systems, composed of just a few nucleons, the bare nucleon-nucleon force could be used to pursue an ambitious programme of determining nuclear properties using recently developed many-body theories. These methods include Variational Monte-Carlo (VMC) and Green's Function Monte-Carlo (GFMC) allowing the first fully microscopic calculations based on realistic interactions supplemented by three-body forces. With a view to the study of very light and few-nucleon systems, another line of approach is the large-basis no-core shell-model (LBSM) which attempts to demonstrate that the shell model combined with a microscopic effective interaction is capable of providing good agreement with the experimental properties of the ground state and low-lying excited states. These state-of-the-art calculations are very successful in describing the structure of bound light nuclei up to mass 10 and important lessons have been learned from this pioneering work. For example, the VMC-plus-GFMC calculations for mass A=6 systems do produce an alpha-like core object and, the description of nuclei beyond deuterium requires a three-body component for the nuclear force. Recent progress in extracting these three-body forces using chiral perturbation theory has been made.

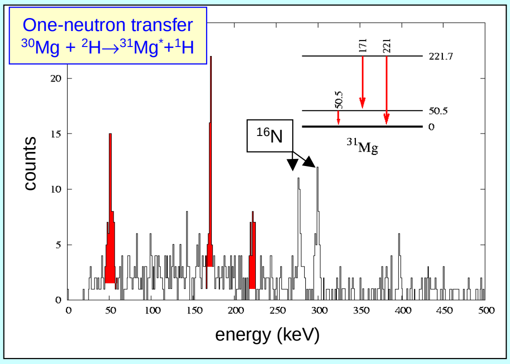
Unbound nuclei, e.g. ^{7}He, still constitute a challenge due to the importance of the continuum. In the context of mass A=8 and 10 systems, the LBSM approach is hampered by the use of shell-model single-particle wave functions with incorrect asymptotics. It is clear that the shell model, used that way, will encounter some

First Results from SPIRAL and REX-ISOLDE

Recently, two new ISOL-based radioactive ion-beam facilities have produced their first results. Post-accelerated radioactive ion beams were produced at GANIL and at CERN. Although very different concepts were used to produce the beams, these results, together with those obtained at ORNL (U.S.A.) and TRIUMF (Canada), prove convincingly the feasibility of the ISOL method to produce high-quality radioactive ion beams and to use them in conjunction with highly segmented germanium-arrays.



At the SPIRAL facility of GANIL, radioactive beams of helium, neon and krypton isotopes were produced through beam fragmentation and after ionisation in an ECR ion source were subsequently accelerated in a cyclotron. Coulomb-excitation measurements of ^{76}Kr($T_{1/2}$=14.6 h) were performed with a beam of 500,000 particles per second and beam energies between 2.6 and 4.4 MeV/u. The γ-rays were detected with the EXOGAM array. The de-excitation of low-lying states in ^{76}Kr is clearly observed in an almost background-free spectrum.



At ISOLDE, radioactive beams of lithium, sodium and magnesium were produced by post-accelerating the 60 keV ISOLDE beams from target spallation using a combined Penning-trap, EBIS and linear accelerator to a specific energy of 2.23 MeV/u. The spectrum shows the results from a laser ionised ^{30}Mg ($T_{1/2}$=0.3 s) beam of 10,000 particles per second on a deuterated polyethylene target. Excited states in ^{31}Mg are populated and the de-exciting γ-rays were detected with the MINIBALL array. The peaks labeled ^{16}N are from the decay of excited levels in ^{16}N produced in transfer reactions on the ^{15}N beam contamination.

problems when describing weakly bound states or resonances. Moreover, the size of the VMC-plus-GFMC and LBSM calculations grows beyond what is manageable at present for nuclei beyond mass A = 10, like, e.g., ^{11}Li.

It is possible however, to explore few-body characteristics that have an overwhelming influence on the precise nuclear-structure properties of light nuclei (beyond mass A=8) by explicitly constructing them from binary and, even more complicated, cluster structures using Faddeev techniques. Since 1990 halo models have been developed where the nucleon-nucleon (NN) degree of freedom is no longer frozen, but chosen in accordance with the free NN interaction prompted by the dilute character of the halo. Thus, focus has been shifted to features genuinely related to the intrinsic character of the halo and the interplay between halo and core degrees of freedom. Studies connecting the three-body models and forces to *ab-initio* calculations, exploring the transitions from distributions in ordinary nuclei to the appearance of cluster structures at and beyond the neutron drip line, are underway and should continue.

Finite quantum few-body systems and correlations between fermions form a field where cross fertilisation takes place between nuclear physics and other fields from atomic, molecular and solid-state physics to hadron physics and astrophysics. A very nice and illustrative example is the study of Bose-Einstein condensates.

6.2.4 Complex nuclei

Mean-field methods: accomplishments and limitations

The main goal of a self-consistent mean-field approach is to look for a fundamental derivation of the phenomenological mean fields used in many approaches, and to determine basic features of two-body effective forces that would give the best mean fields. The mean field is generated by the mutual interactions between all nucleons, and starting from a bare interaction it can, in principle, be calculated using the

Brueckner-Hartree-Fock (BHF) theory and resonating group methods.

To handle the difficulties posed by the repulsive core, and to obtain a correct description of binding energies, a density-dependent HF method was devised based on a local-density approximation. This method has demonstrated the need for dressing the bare nucleon-nucleon force in the presence of the nuclear medium. In practice, the effective interactions used contain a few parameters (zero-range forces, velocity-dependent Skyrme forces, finite-range forces,. . .) that are fixed by the nuclear matter properties and the properties of a few magic nuclei. In this approach, the nucleus chooses its own equilibrium shape and the optimal mean fields for particles and holes (Hartree Fock: HF) and quasi-particles (Hartree Fock Bogoliubov: HFB). This method has been extremely successful for the description of nuclear bulk properties. The self-consistent inclusion of correlations within a random-phase approximation has enabled information about nuclear low-lying collective excitations (vibrations, rotations, shape coexistence, fission paths of strongly deformed nuclei,. . .) to be obtained.

Because the proton-neutron attraction plays such a dominant role in the effective nucleon-nucleon interaction, the neutron mean field depends most strongly on the proton density and vice versa. As a consequence, for nuclei with an extreme neutron excess an increased neutron density in the surface region leads to a weakening of the neutron mean field in this outer region while in the nuclear central part, the neutron mean field is strong and determined by the local proton density. These opposing tendencies in the radial structure of the neutron mean field will make a more complicated field compared to nuclei in regions near stability. In other words, one needs to pin down the isovector density as precisely as possible. These effects might imply a more gradual decrease of the neutron average potential from the central zone in the nucleus towards large radial values, much like the harmonic-oscillator potential. This can have drastic effects on the precise nuclear shell structure that in turn determines how orbitals are filled affecting ultimately the nuclear densities, making self-consistency arguments imperative.

It is therefore essential to map out the evolution in single-particle structure while moving towards more neutron-rich nuclei for not only light, but medium-heavy and heavy systems as well. The study of odd-mass nuclei far from stability through β-decay and transfer reactions, gives access to the precise underlying shell-structure and should be continued at the existing and planned RIB facilities (e.g., approaching the ^{78}Ni region, producing very neutron-rich nuclei around N=28,..).

When approaching the very neutron-rich regions, barely bound nuclei characterised by a low-density surface region mainly occupied by neutrons, will be encountered. The treatment of the HF component (the monopole and quadrupole parts in particular) and the pairing field, that scatters pairs of nucleons into unbound states, such that continuum effects start to play an important role, creates a serious complexity. The way to solve this problem is not currently known and extrapolations from known regions near stability can hardly be expected to converge to give the correct answer to this question.

At the same time, relativistic mean field (RMF) methods, based on phenomenological Lagrangians, have been explored. Applications range from the role of relativity in bound nucleon dynamics to high-spin physics and collective modes in heavy deformed nuclei. These methods can also lend themselves to the study of the origin of pseudo-spin symmetry in medium-heavy nuclei and of the spin-orbit and non-local Darwin terms of the equivalent Schrödinger picture. Although many properties have been explored starting from non-relativistic methods, it is most interesting to deepen our understanding of Dirac's equation for bound particles inside atomic nuclei. The RMF approach, with its emphasis on strong Lorentz scalar and vector fields in the nucleus, provides a useful link between phenomenological descriptions and more basic formulations based on QCD. Microscopic field-theoretical methods, describing the relevant degrees of freedom in the low-momentum regions in terms of meson exchange, may bridge this gap.

The nuclear shell model

Large-scale shell-model studies Modern large-scale shell-model calculations try to incorporate many if not all of the possible ways in which nucleons can be distributed over the available single-particle orbitals. In this way, one can distinguish in the light-mass region, the very light nuclei for which the 1s orbital is the only one. Here of course, problems arise in determining a central field (see section 6.2.4). The next region considers nuclei in the 1p shell, spanning nuclei from ^{4}He to ^{16}O, and similarly in the sd shell model with nuclei from ^{16}O to ^{40}Ca. The current shell-model codes successfully predict excitations in these mass regions in a $0\hbar\omega$ model space without any need for model truncations. The effective forces used are optimised with respect to a particular model space.

Recently, the full fp shell nuclei have been studied in much detail by the Strasbourg-Madrid group using the codes ANTOINE and NATHAN. These state-of-the-art codes have been developed over the last two decades and allow issues like the shell closure in ^{56}Ni and related topics to be considered in a more sophisticated way then previously.

There are a number of problems though that have gradually come into focus as these developments continue and are connected to moving far out from the region of β stability. The question relates in particular to building huge model spaces within a given $0\hbar\omega$ model space with dimensions reaching 10^9. Even in this approach, core excitations are effectively taken into account through the use of effective charges and g-factors. Experimental data further away from stability have shown serious deviations from the results obtained from these large-scale shell-model studies (e.g., the N=20 sodium, magnesium,... nuclei). Moreover, the continued effort to increase the model space might reveal unexpected ways for the nucleons to organise themselves and could hint to new modes of excitation even at very low energies. Here, we think of the already large amount of experimental data showing a new class of states that can "intrude" to low energies thereby bringing in new phenomena from outside the lowest-order shell-model truncation. The most dramatic examples are seen in the very neutron deficient nuclei in the lead region, and for light very neutron-rich N=20 and N=28 nuclei.

It has nevertheless become clear that such approaches have their limitations in the description of medium-heavy and heavy unstable nuclei. This should, however, not be seen as a drawback but as an interesting indicator for unexpected physics. For example, if one uses the spherical shell-model as fully as possible in a given mass region, and encounters systematic deviations between experiment and theory, one may take this as a fingerprint for changing structure. This argument is particularly important when carrying out series of calculations in unknown territories of nuclei far from stability.

Currently, new approaches to handle the large-scale nuclear shell-model problem using a density matrix renormalisation technique and a Monte-Carlo truncation to the nuclear shell-model diagonalisation are under development and have been successfully applied in different regions of the nuclear chart (see next subsection).

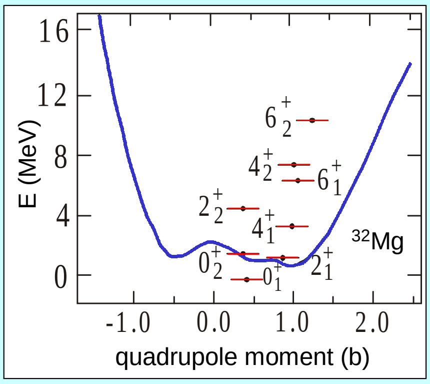
The large number of specific truncation methods are not described here only that the importance for constructing robust methods that allow meaningful extrapolations outside of the region of stability should be stressed. Information from new experimental efforts, using e.g. RIB, are needed to validate certain truncation methods or to find their limitations.

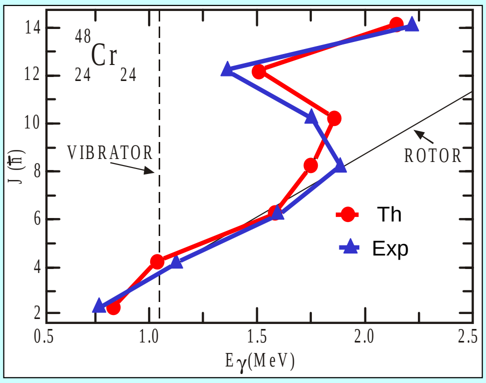
Monte-Carlo shell-model methods A central element in the study of atomic nuclei, that shall be at the focus of the new RIB facilities, is related to the question of how the underlying structure of atomic nuclei will be modified as a function of "external parameters" such as J,T and N/Z. How will the concept of a central field and the derived properties change when *heating* the nucleus to high temperatures, that replicate stellar conditions or when introducing large amounts of *angular momentum* or chang-

Merging Mean-Field and Shell-Model Methods

Nuclear mean fields are generated in a self-consistent way by using effective two-body nucleon-nucleon forces acting between all nucleons inside the nucleus. Using Hartree-Fock or Hartree-Fock-Bogoliubov techniques, both the equilibrium shape and the optimal mean field for (quasi-) particles is obtained. By performing configuration mixing of angular-momentum and particle-number projected self-consistent mean-field states, detailed nuclear-structure properties (energy spectra, electromagnetic properties,...) are generated. A calculation for ^{32}Mg shows the quadrupole deformation energy curve (blue line). The energy reference is that of the lowest lying 0^+ state. These achievements are for the lowest-lying states on the same footing as nuclear shell-model results.

The nuclear shell model essentially starts from closed shells (the known magic numbers at 2,8,20,28,50,82,..) in order to separate the huge many-particle Hilbert space into an inert core and a number of valence nucleons. The latter are distributed in all possible partitions over a limited number of shell-model single-particle orbitals. Using an effective force, adjusted to a given mass region, this approach has been very successful. During the last decade, the dimensions of the calculations have increased by at least two orders of magnitude and collective effects in nuclei away from closed shells have been reproduced (e.g. ^{48}Cr). In order to go beyond mass 60 to 70 a Monte-Carlo shell-model approach has been developed. Up to now, mean-field methods were used to describe these medium-heavy nuclei, but with the new developments the shell model is catching up.





ing drastically the *proton and neutron numbers* from those near stability? As an illustration, one should address the question at which point a spherical shell-structure disappears when a large amount of excitation energy is put into a nucleus.

A formalism that takes temperature, angular momentum as well as the proton-neutron asymmetry into account may well be a fruitful path to follow. All the more so, since at these higher energies one is in principle not able to follow all the individual nucleons in the interacting nuclear many-body system. Very similar to the way in which statistical averages build a bridge between microscopic and macroscopic variables (average particle velocity distribution on the one side and pressure, temperature on the other side); one should concentrate on the thermodynamics of the atomic nucleus.

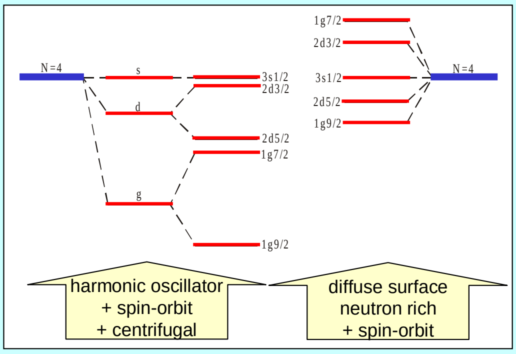
Statistical fluctuations in the level sequences (e.g. compound nuclear resonances, low-lying excited states) contain important information on the nuclear dynamics. The study of quantum manifestations of classical chaos has received much attention in recent years. Starting from Random Matrix Theory (RMT) and the subsequent Gaussian Orthogonal Ensemble (for time-reversal invariant systems) and Gaussian Unitary Ensemble level distributions, statistical analyses of experimental nuclear-structure properties have shed light on how regular dynamics can be discriminated from those more random in nature. Such methods apply to other systems also (atoms, disordered solids).

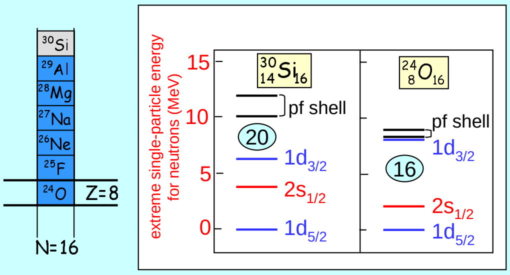
Shell-model Monte-Carlo (SMMC) methods have been developed to a high level of sophistication in order to determine the nuclear partition function and derived quantities such as sum rules for various external fields interacting with a heated atomic nucleus. There may well be general ways to use some of the essential elements of the SMMC methods to derive the analogous classical observables that appear in systems at rapid rotation, those far from stability or any combination of the two. This is almost an unknown territory to be explored in the coming

Changing Magic Numbers

Magic closed-shell numbers (N or Z = 2,8,20,28,50,82 and 126) are well established for nuclei near the region of β-stability. They are predicted by the spherical shell model that approximates the nuclear potential by a self-consistent mean field as derived microscopically from Hartree-Fock Bogoliubov theory (see left part of the figure below which is drawn for a harmonic oscillator potential). The ordering of proton (neutron) energies will strongly depend on the filling of neutron (proton) orbitals through the self-energy Hartree-Fock correction based on the monopole part of the interaction.
When approaching the neutron-drip line, a more gradual decrease of the neutron average potential towards large radial values might occur. This can have drastic effects on the nuclear shell structure, even changing magic numbers (see right part of the figure below).

The monopole part of the effective force induces drastic changes in the single-particle energies resulting in changes in the magic numbers far from the line of stability. By studying, e.g., shifts in single-particle energies in light nuclei, it was shown that the neutron magic numbers at N = 8,20 seem to change into N = 6,16 respectively. This is in agreement with the changes observed in the ordering of shells for neutron-rich light nuclei and seems to originate from the strong attractive π–ν interaction between spin-orbit partners. This particular mechanism hints at an overall modification of standard values of closed shells.





The figure compares the stable isotope ^{30}Si with the exotic nucleus ^{24}O. The former nucleus has 6 protons outside the closed Z=8 shell, while the latter has a closed proton-shell configuration. Due to the monopole part of the effective $\pi d_{5/2}$–$\nu d_{3/2}$ interaction, the well known N=20 gap is reduced and a new gap appears at N=16.

years. These methods may well help extrapolating mean-field and shell-model studies to nuclei far from stability (see boxes “Merging Mean-Field and Shell-Model Methods” and “Changing Magic Numbers”).

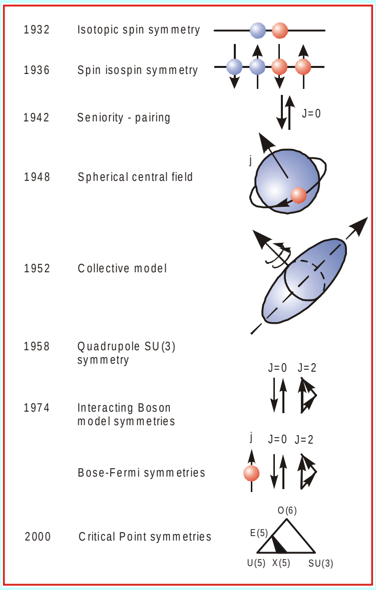
Symmetries in the nuclear many-body system

The concept of symmetries is a very central theme in physics and has given us a deep insight into the interrelationships between different areas of the subject. Symmetry concepts have also guided the progress of nuclear physics over the years as illustrated in a schematic way in the box “Symmetries: Recent Achievements”.

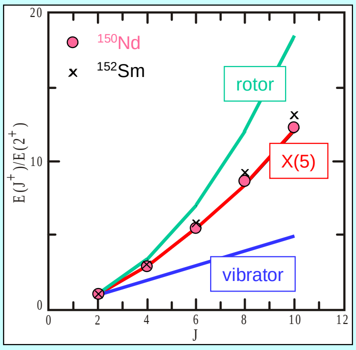
Using simple formulations (e.g., the concept of an interacting boson model (IBM) using s- and d-bosons with its variants and extensions), results with high predictive power were obtained. The suggestion and subsequent discovery of scissors-like motion in strongly deformed nuclei and a class of mixed-symmetry excitations near closed shells was based on symmetry considerations. More recently, such excitations have been suggested for nuclei with a large neutron excess. Symmetry dictated truncations have also allowed algebraic formulations to treat shape coexistence and the appearance of various shapes in a single nucleus. Examples from the very neutron-deficient platinum to polonium nuclei illustrate this issue nicely. Combining bosons and fermions within a global supersymmetric group structure that describes bosonic and fermionic systems with the same Hamiltonian, an elegant description of quartets of nuclei (even-even, the two odd-mass and odd-odd nuclei) is obtained, starting from a single Hamiltonian. Painstaking investigation of the complex structures of the odd-odd member of such a quartet - ^{196}Au - has provided confirmation of these theoretical predictions. Recently, a lot of interest also has been steered up by in the topic of quantum phase transitions and phase coexistence in systems with a finite number of constituents. It has become clear that by approximating the potential in the (β, γ) Bohr-Mottelson parameter space, a number of solv-

Symmetries: Recent Achievements

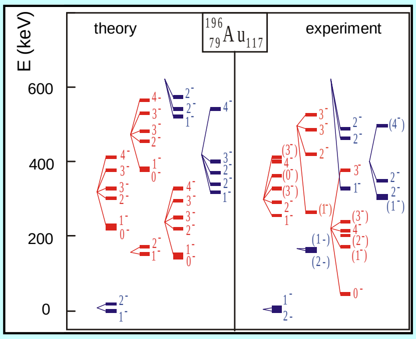
The concept of symmetries in physics has always been central to the unification of different phenomena. The following figures give an overview of a number of symmetry realisations characterising the nuclear-many body problem, going all the way from the initial isospin classification scheme of nucleons, in 1932 by Heisenberg, to recent discussions on critical-point symmetries in studying nuclear-physics transitions.



For particular choices of the nuclear potential energy surface in the collective (β,γ)-plane, exact solutions to the Bohr-Mottelson model have been obtained (called X(5) and E(5) critical-point symmetries). The isotopes ^{150}Nd and ^{152}Sm are good candidates for X(5) symmetry as shown in the figure where the X(5) solution is compared to a rotor and a vibrator.



Through supersymmetry, bosonic and fermionic systems with a constant N (the sum of the number of bosons (paired nucleons) and the number of fermions (unpaired nucleons)) are described simultaneously. The predictive power is shown for the case of ^{196}Au.



able models emerge, the so-called critical-point symmetries. Both experimental and theoretical studies will thus tread on fertile ground for future explorations.

6.3 Recent experimental achievements and future outlook

The last five years have witnessed a number of remarkable achievements. New RIB facilities have been commissioned and have produced their first results, fragment separators and storage rings have provided an increase in yield and large γ-ray arrays (like EUROBALL) have become fully operational and have been used extensively for detailed in-beam and reaction studies. The first germanium arrays based on electronically segmented detectors (like the MINIBALL detector and EXOGAM) have been used for pioneering experiments with RIB (see box "First Results from SPIRAL and REX-ISOLDE") and some ingenious new instrumentation, like radio-frequency coolers, has allowed very interesting experiments.

In Europe, two major second-generation facilities for the production and use of radioactive ion beams have been proposed: "An International Accelerator Facility for Beams of Ions and Antiprotons" (at GSI) and "A European Isotope Separator On-Line" (EURISOL). Both these projects should become operational within a decade and provide the anchor to which the long-term future of nuclear-structure research is secured. In the medium term, a vigorous programme to upgrade and exploit the existing instrumentation should be undertaken in combination with the necessary R&D for the second-generation facilities.

In this chapter a selection from the rich diversity of recent experimental achievements is presented. It is not intended to be complete but rather to offer some examples to indicate future developments.

6.3.1 Extreme proton-to-neutron ratios

Masses, ground- and isomeric-state properties

Masses, ground- and isomeric-state properties and decay modes are often the first experimental information obtained for exotic nuclei and form the backbone of any theory. These types of experiments have always been, and will continue to be, the forerunners of larger experimental campaigns on exotic nuclei. Over the past five years, a wealth of high-quality data has been obtained.

Masses The ground-state mass of the nucleus is a particularly interesting quantity as it encompasses all effects of the interactions and correlations that are involved in the atomic nucleus. Experimental mass accuracies for exotic nuclei now reach values of $\delta m/m = 10^{-6}$ to 10^{-8} (see box “Masses”) and are often at least an order of magnitude more accurate than the deviations between experiment and microscopically based mean-field calculations. Masses of very neutron-rich nuclei form an ideal testing ground to determine the density dependence of the effective interaction however extrapolations of the calculations outside the region of known masses fail. More precise mass values are needed as comparisons of quantities derived from mass differences with systematic trends might uncover subtle nuclear-structure effects: changes in the shell structure, ground-state correlations, changes in pairing energy, etc. Mass measurements should be vigorously continued in the future.

New projects to measure the mass of the heaviest elements (using e.g. the SHIPTRAP set-up), to attain even greater accuracies using higher charge-state ions and to reach ever shorter-lived nuclei are being developed. In order to go even further towards the neutron drip line for heavier atoms, the intensities and purities offered by the second-generation facilities will be essential.

Charge radii and moments Laser spectroscopy, using isotope shifts and hyperfine structure of atomic transitions to determine charge radii and nuclear moments, has traditionally been a very successful field using beams from ISOL systems. A continuous improvement in experimental techniques over the last few years has led to new opportunities. For example, results have been obtained for the transuranium elements and for very light masses with their large mass shifts, as well as for refractory elements by using laser desorption or a cooler device combined with the IGISOL technique. Reliable isotope-shift data have thus been obtained for light elements (like, e.g., the neon isotopes). These data provide an extreme point to test large-scale shell-model calculations. The use of laser ion sources at ISOL facilities has opened up new opportunities for laser spectroscopy measurements with lower accuracy but with unprecedented sensitivity. In addition, a new technique, already in use, that exploits the natural orientation/polarisation/alignment of a fragmentation reaction has been used to determine moments of ground states and isomeric states. All these techniques should be pursued and consolidated in the future.

Information on nuclear charge radii and diffuseness (the latter is not accessible by the above mentioned methods) can be obtained from electron-nucleus elastic scattering. Electron-nucleus colliders (eA) where the exotic nuclei are stored in a cooler-storage ring that is intercepted by an intense beam of electrons from an electron-storage ring are being considered on the longer term. By also studying inelastic collisions, detailed information on the collective motion of exotic nuclei and, at higher energy, even on the single-particle structure can be obtained. These very promising but challenging ideas introduced here, e.g. in the context of the new GSI-accelerator complex, should be developed and explored.

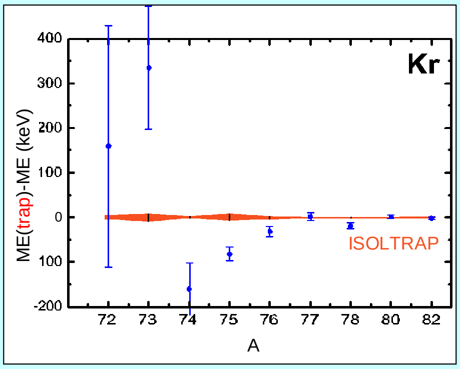
Shapes, symmetries and low-lying excitations

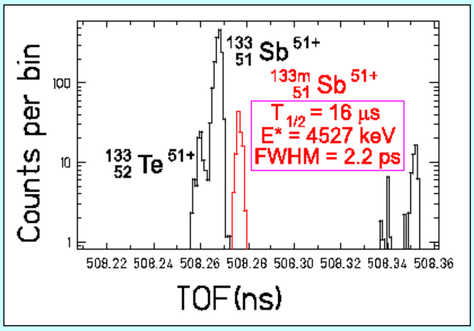
One of the most fruitful avenues in recent years has been the application of dynamical symmetries to the nuclear-structure problem. The method, equally applicable in many other fields, focuses on the basic states of motion available

Masses

Different mass-measuring techniques have been exploited over the last five years and have produced results with high accuracy over a wide variety of radioactive isotopes. Even the shortest-lived isotopes have been studied. Experiments at ISOLDE where three ion traps are coupled in a row (one RF- trap and two Penning traps) have enlarged the mass-measuring capabilities to essentially every isotope an ISOL system can deliver. This resulted, e.g., in mass measurements of isotopes with half lives as short as 98 ms (^{32}Ar) and 65 ms (^{74}Rb) and this with an unprecedented precision of $\delta m/m = 10^{-8}$. Using time-of-flight techniques and frequency measurements, large data sets have been obtained at the GSI-ESR storage ring on heavier masses while lighter masses were measured using the GANIL cyclotrons and spectrometers and the MISTRAL spectrometer.

The deviation between new mass values obtained at ISOLDE and previous results (blue data points) are shown for some neutron-deficient Kr isotopes. The uncertainty of the new data (red coloured band) is almost constant for all radioactive isotopes. The mass of ^{72}Kr ($T_{1/2}$=17 s) is important for nuclear astrophysics as this isotope is expected to be a waiting-point nucleus in the rp-nucleosynthesis process.





A preliminary spectrum from a time-of-flight mass measurement at the GSI storage ring is shown. The ground state of ^{133}Sb is separated from its isomer ($T_{1/2}$= 16 µs in the neutral state). The sensitivity of these measurements has been increased to a level where single-ion experiments on exotic nuclei become possible.

to a system and the relative motion of different classes of its constituents, rather than on the motion of the individual constituents themselves. Thus the symmetries being applied to the nuclear-structure problem are equally relevant in the realm of molecular or particle physics.

A dynamical symmetry provides an analytic solution for the low-lying collective states of a nucleus in a specific limit which corresponds, in microscopic terms, to a particular mean shape. However, the interplay of the constituent valence particles in specific orbitals can sometimes result in two minima in the potential energy surface corresponding to two very different shapes, yet still close enough in energy for both sets of states to be observed. Examples of this shape co-existence between spherical and axially deformed structures are well known (Figure 6.3). These nuclei can be used to probe how small changes in the properties of the last few valence particles can result in major changes in the shape and hence the mean field of the nucleus.

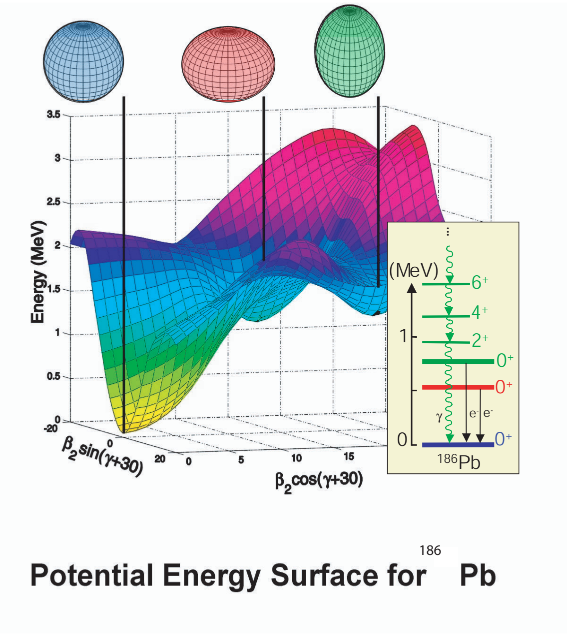


Figure 6.3: Total potential-energy surface for ^{186}Pb. The three lowest 0^+ states of ^{186}Pb, identified in the α decay of ^{190}Po, correspond to the three minima in the potential energy surface at spherical (blue), oblate (red) and prolate (green) deformation.

A wealth of data on low-lying collective excitations and yrast states has been obtained by using the recoil-decay tagging techniques and the spectroscopy of fission products such as was performed at ILL. Decay studies have experienced a revival in recent years thanks to the use of segmented detection systems for particles (e.g. β-delayed single and multi-proton and -neutron, deuteron and α emission). These studies give, through the selective nature of β and α decay, detailed information on the low-lying collective and single-particle structure of nuclei. Moreover, the addition of γ-ray tracking devices and the ever increasing intensity and purity of RIB will allow such studies to be launched in totally unexplored regions of the nuclear chart. Also, Coulomb-excitation measurements and few-nucleon transfer reactions with energetic radioactive beams will help unravel the low-energy structure of exotic nuclei; first experiments have already shown promising results (see box "First Results from SPIRAL and REX-ISOLDE"). These techniques that were used extensively in the past with stable isotope beams will now be used intensively again at the new facilities. Although the methods are well known, they have to be adapted to cope with the inherent lower RIB intensities, the use of inverse kinematics and the radioactive background produced by scattered or stopped particles from the beam. For example, mapping the structure around the doubly magic ^{132}Sn nucleus (in the mid-term future) and around ^{78}Ni and ^{100}Sn (in the long-term future using second-generation RIB facilities) will become possible. This particular information represents one of the most important benchmarks for nuclear-structure models far out from stability.

Unbound systems and the lightest nuclei

The past years have deepened our understanding of exotic light nuclei, both through studies of known nuclei and various phenomena, and through excursions into unknown territory. The mapping of the position of the neutron drip line is continuing and the frontier is presently at ^{31}F, ^{34}Ne (perhaps the most neutron-rich isotopes of these elements) and ^{37}Na. Several general surveys have given a much better basis for evaluating trends in the structure of light nuclei. Very important in this respect are the measurements of interaction cross sections, from which matter radii are deduced. These measurements have currently reached magnesium and have also been performed for the chlorine and argon isotope chains. Combining such results with measurements of charge radii indicates that neutron and proton "skins" build up as we go away from the line of β-stability. Similar information was obtained from one-neutron knockout reactions studied over extended chains of isotopes. For instance, nitrogen, oxygen and fluorine nuclei with neutron numbers 15 and 16 deviate from systematic trends, presumably due to s-neutrons in outer orbits. Such nuclei display features that in several respects are similar to those of halo nuclei, but clearly have a more complex structure involving, e.g., core modifications. Meanwhile, new techniques have been exploited to access nuclear matter distributions in a more refined manner. Neutron interferometry techniques have been used to deduce the size of the halo itself and proton elastic scattering at relativistic energies was recently shown to be a useful tool for revealing matter distributions of halo nuclei.

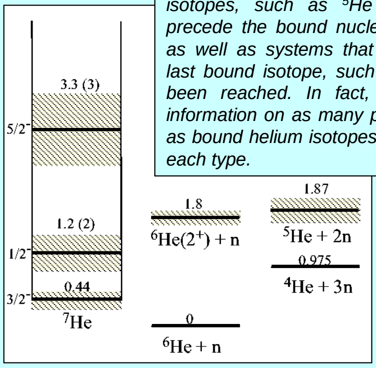
Halos are by now well established among the light (neutron) drip-line nuclei. More recently, halo states in heavier nuclei have been found, one example being ^{19}C. For the known halo states, such as ^{6}He and ^{11}Li, complete kinematics experiments have allowed the introduction of new analysis methods: angular distributions among outgoing fragments have provided stringent tests both of the reaction mechanism and of the nuclear structure. Another important experimental tool has been the recording of γ rays de-exciting the outgoing fragments from halo break-up reactions. From such measurements one is able to deduce precise single-particle occupancies as well as the effects of core-modifications in a halo state. Results of this kind now provide us with a rather detailed understanding of how halos are formed in nuclei.

Progress has also been made in other areas more distantly related to neutron halos and skins. A more general search for cluster structures in nuclei has continued, yielding interest-

Beyond the Drip Line

The energy gain when nucleons occur in pairs makes the drip lines look “jagged”, the isotope (isotone) lines with even Z (N) often extend further out than the odd ones. Nuclei beyond the drip lines, i.e. nuclei where one- or two-nucleon emission is possible from the ground state, can now in several regions of the nuclear chart be accessed experimentally. The information on the decay mechanism, in particular when two-proton emission takes place, as well as on other nuclear-structure properties are of particular interest.

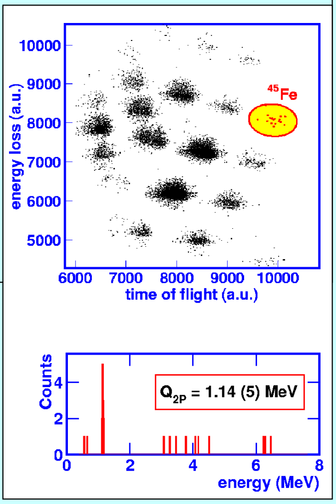
Both “missing systems” of the helium isotopes, such as ^{5}He and ^{7}He that precede the bound nuclei ^{6}He and ^{8}He, as well as systems that go beyond the last bound isotope, such as ^{9,10}He have been reached. In fact, we now have information on as many particle unbound as bound helium isotopes, namely four of each type.



Ground state and recently identified excited states in ^{7}He are compared to core plus one, two or three neutron states. The excitation energy relative to the ^{6}He+n system is given in MeV.

Ground state one-proton radioactivity was first seen about 20 years ago and the experimental activity has accelerated during the last decade. This decay has now been seen in most odd-Z elements between iodine and bismuth. It has been developed into a powerful spectroscopic tool, e.g. for the determination of spectroscopic factors. Even excited states of g.s. proton emitting nuclei have been studied resulting in detailed nuclear-structure information beyond the drip line.

The first evidence for ground state two-proton radioactivity, predicted about 40 years ago, appeared very recently for ^{45}Fe after a decade of experimental campaigns. Future detailed studies of the individual proton energies and their relative emission angle could provide information on the nucleon-nucleon correlation in medium mass nuclei.



Projectile-fragmentation experiments at GANIL and GSI have identified the nucleus ^{45}Fe by measuring the time-of-flight and energy loss of each ^{45}Fe atom as well as its decay. The peak at 1.14 MeV in the ^{45}Fe correlated decay spectrum indicates that this nucleus disintegrates by two-proton emission from its ground state.

ing results, e.g., for the excited states in ^{10,12}Be. The problem of the multi-particle continuum structure has been attacked from several angles, both experimentally and theoretically, but so far mainly for proton-rich nuclei. Beyond the proton drip line some two-proton emitters (e.g. ^{12}O) have been characterised through reaction work and recently, the first experimental evidence of ground state two-proton radioactivity has been reported (see box “Beyond the Drip Line”). Just within the drip line, several nuclei (e.g. ^{9}C and ^{12}N) exhibiting β-delayed multi-particle decay modes have been studied. So far most results are compatible with sequential decays nevertheless, one should note the theoretical improvements in predicting true three-body decays.

Nuclear systems just beyond the drip lines have been studied in a more general way. Both drip lines appear “jagged” (for the proton drip line starting above oxygen) in the sense that ^{4}He for example cannot bind one or three neutrons, but does bind two and four. The “missing systems”, such as ^{5}He, ^{10}Li or ^{13}Be, are important for understanding the local structure in detail. At the same time, one has also reached beyond the last bound nuclei on both sides, examples being ^{10,11}N and ^{9,10}He. More recently, interesting results have also been reported on the very light systems ^{5}H and ^{4}n, where the neutron to proton ratio approaches that of neutron stars. Although the neutron drip line is currently out of reach for the heavier elements, the proton drip line has been surpassed in many instances although for heavier nuclei at the moment only for odd Z (see box “Beyond the Drip Line”).

It is not yet known how far up in Z and A halos exist nor how abundant they are in spite of the theoretical attempts made at answering these questions. The conditions for finding the extremely extended Efimov states in nuclei are being narrowed down, but we are still some way from having definite predictions that would pinpoint their location. A larger problem involves the neutron and proton skin nuclei, where much work still remains, experimentally as well as theoretically. Future experiments in this direction require new facilities that can provide the necessary increased beam intensities. The coming period could be envisaged as a time of consolidation and gradual expansion, looking, e.g., into the exploitation of these features in more stable nuclei.

Clustering and exotic shapes

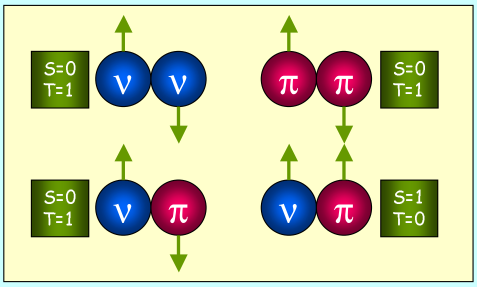
Nuclear clustering based on α particles and strongly bound substructures with N=Z has been studied for many decades. The recently regained interest has focused on loosely bound systems through the study of exotic nuclei and in particular on states whose energies lie close to the threshold for decay into substructures. The physics of drip-line nuclei, where single-nucleon and cluster binding energies are very small, is strongly related to the clustering phenomena observed at the single-nucleon and cluster thresholds in normal nuclei. The existence of strongly deformed shapes - such as super- and hyperdeformation - in light nuclei has also been recognised to be as being related to clustering phenomena. Even octupole and higher-order deformations are considered and bring concepts of intrinsically reflection-asymmetric molecular structures into play. Cluster states are often very peculiar and many examples show that they cannot be obtained even in the largest shell-model calculations. The nuclear properties of cluster states can be described in terms of anti-symmetrised molecular-dynamics. Other approaches, whereby explicit molecular concepts involving neutrons in covalent binding orbits are considered, are also employed.

The spectroscopy of strongly deformed (exotic) shapes in N=Z nuclei has thus far been the domain of charged-particle spectroscopy which has yielded evidence for states characterised by the emission of α-particles, ^{8}Be and heavier fragments. However, new detector set-ups with combined particle-γ detection are expected to give new insight into exotic shapes of nuclei, which may be related to clustering. On the neutron-rich side, the weakly-bound nuclei also show a strong tendency for clustering. This appears to be due to properties of the residual interaction which leads to a maximum overlap of protons with neutrons. Furthermore, in nuclei with a large neutron excess, valence neutrons and protons occupy very different single-particle orbits which in turn may drive the nucleus towards non-identical proton and neutron deformations, a feature for which some evidence has already been found in stable nuclei. Inelastic excitations of low-lying collective states, separating the isovector and isoscalar transitions by means of appropriate probes, allow to access experimentally this appealing feature.

6.3.2 Isospin as a degree of freedom

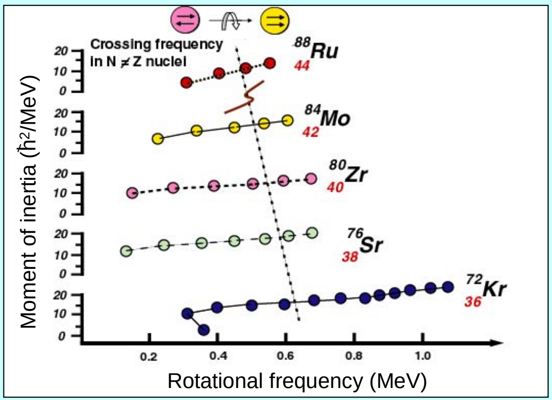
Nuclei along the N=Z line display several unique characteristics which arise from two principal sources. Firstly, the coincidence of neutron and proton Fermi energies ensures maximum spatial overlap between the neutron and proton wave functions so that, as the number of valence nucleons increases with increasing mass, strong collective effects develop. Secondly, the charge independence of the nuclear force gives rise to a neutron-proton symmetry represented by the isospin quantum number and which manifests itself in a number of structural features observable only on, or very near, the N=Z line. Examples include SU(4) symmetry, which holds only for the lightest nuclei and rapidly detoriates as the spin-orbit force increases, mirror symmetry, which is currently being studied to higher spins than ever before, and neutron-proton pairing correlations (see box “Neutron-Proton Pairing: a New Super Fluid Phase of Nuclear Matter”). Breaking of the isospin symmetry itself is expected to occur most strongly for the heaviest masses on the N=Z line. Although the symmetry is already broken to some extent, at the level of the strong interaction and - to a much larger extent - by electromagnetic forces, the overall level of mixing remains small and the isospin formalism remains a very powerful tool in relating the properties of corresponding levels in different nuclei, and to understand the structure of the nuclear wave function.

Neutron-Proton Pairing: a New Super-Fluid Phase of Nuclear Matter



To what extent the T=0 pairing forms a condensate similar to that of the T=1 pairing is still an open question. In deformed nuclear systems, quenching of the pairing field is reflected by an increase in the moment of inertia at high angular momentum. When a pair of nucleons have aligned spins, they are expected to be much more robust against rotation and, anomalies in the particle alignments (the breaking of pairs) should occur. Indeed, experimentally it has been established that the rotational frequency, at which such pairs break in the N=Z (even-even) nuclei, is systematically higher compared to the heavier even-mass isotopes (the dashed line in the figure shows the crossing frequency for the N≠Z nuclei). This might be an indication for the formation of a T=0 pairing condensate.

The ground state of most nuclei is well described in terms of a super-fluid condensate, in which Cooper pairs of neutrons (ν–ν) and protons (π–π) are formed, quite analogous to the electron pairs in superconductors. However, nuclei along the N=Z line exhibit a special 4-fold symmetry in the nuclear-wave functions. Hence, in addition to the standard ν–ν and π–π pairs, one expects the presence of neutron-proton (ν–π) pairs. Since neutrons and protons are different fermions, they can form two different types of Cooper pairs. One corresponds to the standard coupling with total spin (S) zero and isospin (T) equal to one. The other, more exotic, is a coupling which is Pauli forbidden for identical particles (S=1, T=0). The latter coupling is favored by the nuclear interaction as exemplified by the deuteron (a ν–π pair) that is bound only in its T=0 state; the T=1 state is unbound by approximately 200 keV. This preference persists in light N=Z odd-odd nuclei, but reverses at larger Z values.



Isospin symmetries and mirror pairs

The concept of the neutron-proton symmetry, described by the isospin quantum number, leads to the concept of isobaric multiplets and mirror partners, where the energy levels of different members of a multiplet differ only because of the Coulomb force. Isospin symmetry can be studied, through exchange reactions and β decay, by comparing the measured Gamow-Teller strength distribution in mirror nuclei. The availability of intense beams of unstable nuclei close to the N=Z line has initiated an interesting research programme along this line.

Electromagnetic transitions are also a crucial probe. Until the past decade, studies of the Coulomb energy differences (CED), the difference in energy between isobaric analogue states, were focused almost exclusively on the ground states of nuclei. However, in recent years the large increase in sensitivity and resolving power resulting from the advent of large arrays of γ-ray detectors have allowed the study of nuclei with N<Z to ever increasing excitation energies and to extend their study up to medium-heavy nuclei involving the full fp shell and $1g_{9/2}$ shell-model orbits.

By resorting to large-scale shell-model calculations that reproduce the experimental findings very well, several important results have been deduced. Here, the number of active nucleons is large enough to make coherent phenomena important and collective excitations with a simple geometrical interpretation emerge naturally from such calculations. Moreover, it has been suggested that CED can give information on the evolution of nuclear radii along the yrast bands and may even provide direct evidence for charge-symmetry breaking of the nuclear field.

Isospin mixing in medium mass N∼Z nuclei

One of the challenges of modern nuclear physics is the exploration of the limits of validity of the isospin quantum number with increasing values of Z and A. The main contribution to the isospin-symmetry breaking is the Coulomb interaction. Theoretical estimates, limited to the ground states of even-even nuclei, show that the amount of isospin mixing increases with the nuclear mass A and, for a given A, is maximum for N=Z. An understanding of the mechanism of isospin mixing in nuclei close to the N=Z line is crucial in order to perform reliable corrections when deriving the coupling constant from the log(ft) values of superallowed Fermi β decays. In particular, it is not clear whether and how these correction terms vary with increasing A, and it is therefore important to extend the study of isospin violating processes to heavy nuclei all the way to the proton drip line. These measurements might have a direct impact on the unitarity test of the Cabibbo-Kobayashi-Maskawa (CKM) matrix (see section on fundamental interactions). Another possible way to study the violation of isospin symmetry induced by the Coulomb interaction is through the observation of isospin forbidden E1 transitions in even-even N = Z nuclei. Also, measurements on the E1 rates in mirror nuclei might reveal information on the violation of isospin symmetry as, unlike the N=Z case, the isovector amplitude is different from zero and the difference between the mirror E1 strengths is due to the interference between between the isovector term and the term induced by isospin mixing.

To answer these questions an extensive study of the excitations, ground state and decay properties of N=Z nuclei and extremely proton-rich light nuclei is required. Direct reactions using RIB of medium-mass N=Z nuclei should provide a powerful tool for investigating coherent effects in N=Z nuclei such as the interplay between isoscalar and isovector pairing. RIB and intense stable isotope beams for dedicated and long-term experiments, together with the continued development of granular and efficient γ-ray detector arrays (like AGATA) and particle detectors, are necessary requirements for further advances.

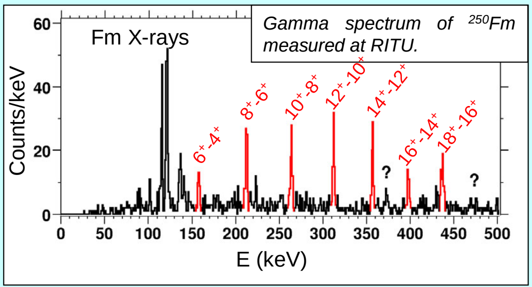
6.3.3 The heaviest nuclei

An obvious way to study the effective nucleon-nucleon interaction is to proceed towards the upper end of the periodic table. Some 35 years ago, the first thorough theoretical studies concerning super-heavy elements (SHE) were published. The predicted existence of these elements far beyond those known at the time was based on nuclear-structure effects. These effects create a barrier against spontaneous fission, which would otherwise terminate the periodic table just above Z=100. The effects of repulsive Coulomb forces and nuclear attraction delicately balance each other in the region of SHE. The level densities are high and nucleonic orbitals with high and low angular momentum occur close together near the Fermi energy. Small shell gaps may cause shape changes such that nuclear deformed states may coexist. These are the main reasons why nuclear-structure effects play an especially important role in this region. They may also have a decisive effect on the possibility of producing these nuclei in fusion reactions. Highlights of recent work include the synthesis of elements up to Z = 112 and the chemical study of isotopes of element 108 (Hs) at GSI using cold fusion reactions with stable isotope beams and targets, and tentative results from Dubna on the synthesis of elements 114 and 116 using hot fusion reactions and radioactive targets (see box "Super-Heavy Elements").

In the near future, the research programmemes on SHE will be focused on the confirmation of the latest results and on detailed spectroscopy in the A=250-270 region. In order to accomplish this, specific development programmes should enable future experiments to cope with higher intensities of stable isotope beams. The successful atomic-physics and chemistry studies should be continued and mass measurements should be initiated. Future directions should also include an evaluation of the merits of hot and cold fusion, the development of dedicated stable isotope beam accelerators that can deliver beam intensities higher by an order of magnitude then those currently available and the use of intense neutron-rich RIB. The latter combined with neutron-rich stable or long-lived radioactive isotope targets might create an opportunity to reach for the first time the unknown region where decay chains of hot fusion products end. In parallel, high-power target and innovative separator developments are needed.

Super-Heavy Elements

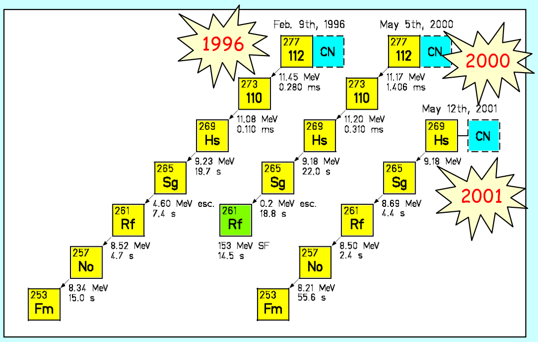
Unique information on the nuclear interaction comes from the study of isotopes of the heaviest elements which are known to exist solely on the basis of quantum effects. The outstanding questions concern the ultimate end of the periodic table and the location of maximum quantum stabilisation. Highlights of recent work are the synthesis of elements up to Z = 112 using cold fusion reactions with stable beams and targets, synthesis and chemical study of isotopes of element 108 (Hs) at GSI and tentative results from Dubna on the synthesis of elements 114 and 116 by using hot fusion reactions and radioactive targets.



Gamma spectrum of ^{250}Fm measured at RITU.

Structure studies of the heaviest nuclides have made rapid progress during the past years. In-beam γ-ray experiments at JYFL and ANL (USA) around ^{254}No have enabled the determination of the ground-state deformation of several nuclides. At JYFL it has been possible to use recoil-decay tagging in conjunction with a recoil separator to observe, for the first time, in-beam conversion electrons from ^{250}Fm and ^{254}No. Such studies will ultimately provide unique information on single-particle states in the transfermium region.

A recent report by the IUPAC/IUPAP Joint Working Party concludes that element 110 has convincingly been identified at GSI in 1994. Subsequent to this report, new data on element 112 have confirmed the 1996 result. In addition, an independent experiment on element 108 (Hs) performed on a one-atom-at-a-time basis using chemistry and nuclear-physics methods has also confirmed the observed element 112 decay chains. Strong relativistic effects on the inner atomic electrons make these elements extremely interesting objects in quantum chemistry.



The first observed decay chain of an isotope of element 112 from the reaction ^{70}Zn + ^{208}Pb (in 1996), compared with the result of the confirmation experiment using SHIP (in 2000) and with one of the chains produced in the chemistry experiment in the reaction ^{26}Mg + ^{248}Cm (in 2001).

6.3.4 High-spins and exotic excitations

Through the response of the nucleus to rotational stress, one can investigate a wide variety of nuclear-structure phenomena that are manifest in a finite fermionic system and provide unique information on the detailed structure of the nuclear potential. The existence of very elongated nuclear shapes and their stabilisation at high angular momentum sheds light on the underlying symmetries characterising the dynamical system.

Breaking of the rotational symmetry can be related to asymmetries in charge or in current distributions. Information on the nuclear properties is encoded in a cascade of about thirty γ-rays de-exciting the highly excited state to the ground state. Large germanium detector arrays, designed to pick out high-multiplicity γ-ray cascades, have provided the identification of discrete nuclear states up to the fission limit and of the high-spin quasi continuum, yielding information on the order-chaos transitions. In particular, superdeformation has attracted interest through the problems of feeding to and decay-out. For example, information on the γ-decay of the giant dipole resonance built on excited states has been obtained for the ^{143}Eu nucleus. Also appealing is the search for a severely elongated, axially symmetric *hyperdeformed* (HD) shape with an axis ratio of 3:1, which is predicted in certain regions. The interplay between reaction dynamics, binding energies and fission barriers to optimise the population of HD structures at the border of reachable angular momentum has received a lot of attention.

Nuclei when rotating may also develop shapes in which the *axial symmetry is broken.* In fact, in contrast to the region around the predominantly axially symmetric ground states, one expects a considerable deviation from such shapes at high spin, because of the effect of the Coriolis and centrifugal forces. The breaking of the axial symmetry in a triaxial nucleus is associated with a low-lying collective motion, called “wobbling mode”, that represents a small-amplitude fluctuation of the rotational axis away from the principal axis such as a precession motion. Although excitations of this type were predicted long ago, only recently they were identified in ^{163}Lu.

Not long ago it was thought that near-spherical nuclei always emitted irregular patterns of γ-rays. However, very regular patterns of γ-rays - and hence possible evidence for rotation - were detected from nuclei that were known to be almost perfect spheres. This behaviour has been termed “magnetic rotation” because the rotational sequences arise from the anisotropy of currents in the nucleus, which produce a magnetic moment. The more familiar rotation of deformed nuclei (and molecules) could be called “electric rotation” to reflect the fact that it results from an anisotropy in the charge distribution.

Spontaneous chiral-symmetry breaking has been discovered in odd-odd nuclei having triaxial shapes related to configurations where the angular momenta of the valence proton, neutron and the core rotation are mutually perpendicular. Such angular momenta can form a left- and a right-handed system, related by the chiral operator which combines time reversal and rotation by 180 degrees. Spontaneous chiral-symmetry breaking in the body-fixed frame is manifested in the lab-frame as a degenerate doublet of ΔI=1 bands.

Research in the field of high-spins and exotic excitations has yielded an impressive amount of high-quality data, while new phenomena appear on the horizon. In the short term, a continuous effort in measurements with highly efficient and segmented γ-ray arrays should be pursued with increased stable isotope beam intensities. In the longer term, the possibilities of RIB could be investigated but this will certainly require the beam intensities expected from the second-generation facilities.

6.3.5 Giant resonances in cold and hot nuclei

Giant resonances in atomic nuclei are collective states, usually at excitation energies above the particle separation energy, built by a coherent motion involving many nucleons. Such resonances can be viewed as high-frequency ($\sim 10^{21}$ s^{-1}) but small-amplitude density or shape vibrations. Various modes are known, differentiated by their multipolarity and spin and isospin quantum numbers. Their unambiguous identification and detailed study required a large arsenal of selective probes, involving γ-absorption, inelastic electron and hadron scattering, charge-exchange reactions, and heavy-ion induced excitations.

The characteristics of giant-resonance excitations are governed essentially by the macroscopic nuclear properties. Depending on the specific mode, they carry information on the nuclear compressibility and viscosity, on the (volume and/or surface) symmetry energy, and on nuclear shape parameters such as radius, deformation or (neutron) skin. In a microscopic description, giant resonances are built by coherent 1p-1h excitations where the excitation energies of the isoscalar and isovector modes are determined by the isoscalar (attractive) and isospin-dependent (repulsive) terms of the effective nucleon-nucleon interaction, respectively.

The increasing sophistication of experimental techniques over the past decade has led to the discovery of new phenomena and answers to long-standing puzzles: identification of the isoscalar dipole resonance; localisation of missing Gamow-Teller strength at high excitation energies; observation of double-phonon dipole and quadrupole resonances probing the harmonicity of the nuclear response; giant dipole resonances reflecting properties of hot nuclei; detailed studies of the damping mechanisms using high-resolution strength-function measurements; first attempts to access the multipole continuum strength of exotic unstable nuclei.

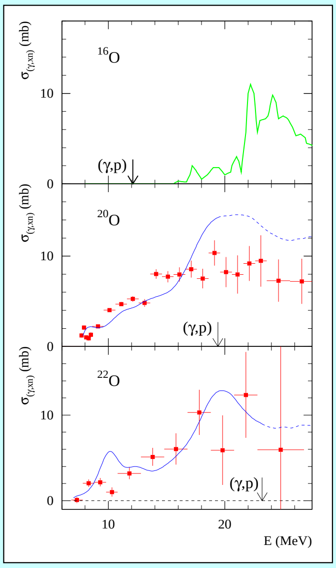
A special class of resonances is induced by the orbital motion of nuclei within the nucleus. Experimentally, they are best studied with high-resolution photon and electron scattering. Recent experimentally confirmed examples are a magnetic dipole mode in deformed nuclei corresponding to a scissors-like vibration of the neutron against the proton distribution, a magnetic quadrupole twist mode, and a low-lying

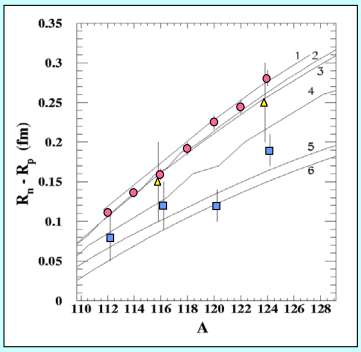
Giant Resonances and Exotic Nuclei

Giant resonances in atomic nuclei are collective states built by a coherent motion involving many nucleons. The past decade has witnessed the discovery of new phenomena and answers to long-standing questions, and first attempts involving exotic nuclei have been undertaken.

Photo-neutron cross sections (the giant-dipole resonance) for the stable N=Z ^{16}O nucleus and the very neutron-rich ^{20,22}O are compared. Absorption of real photons is used for ^{16}O while absorption of virtual photons from Coulomb collisions of 500-600 MeV/u beams on a lead target is used for ^{20,22}O . For the latter two isotopes, the dipole strength appears to be strongly fragmented and extends down to low-excitation energies. The smooth curves represent shell-model calculations performed within a large basis. The proton separation energy threshold is indicated with an arrow (γ,p).

In very neutron-rich nuclei with loosely bound valence neutrons, non-resonant electric multipole strength close to the particle threshold develops. Such a threshold strength was observed in light neutron-rich (halo) nuclei. Accordingly, neutron-capture rates increase, which is of relevance to some nucleo-synthesis processes.





Neutron-skin thickness (R_n-R_p) of tin isotopes as a function of mass number. The full circles, triangles and squares with their error bars are obtained from (^{3}He,t) charge-exchange reactions, inelastic α scattering and from antiproton absorption, respectively. The numbered curves are results of relativistic (1-3) and non-relativistic (4-6) calculations.

electric dipole resonance with toroidal velocity distributions. Their existence is of fundamental interest because they prove that the macroscopic response to the excitation of giant resonances corresponds to that of an elastic medium rather than a fluid. Furthermore, such modes are predicted (and partially already experimentally confirmed) as global phenomena in many-body systems like atomic clusters, Bose-Einstein condensates, atomic Fermi gases and quantum dots.

The isovector giant dipole resonance, owing to its specific selectivity in the γ-decay channel, was observed in hot and rapidly rotating nuclei and has helped to elucidate the bulk properties of (highly) excited nuclear systems. Information was deduced on the evolution of the nuclear shape with temperature and spin, and phenomena such as shape transitions and shape fluctuations were observed. In contrast, the rate at which collisional damping proceeds was found to have a rather weak dependence on temperature. In order to pursue such experiments, the relevant techniques need to be more refined and highly selective. γ-ray detection devices with high efficiency, high multi-hit capability, and full solid-angle coverage, such as the γ-ray tracking device AGATA, would provide a much better definition of the excitation energy and spin domains from which the giant resonance decay occurs.

Giant resonances in exotic nuclei are a topic of current and future interest in nuclear-structure physics. A considerable amount of theoretical work is being devoted to this subject. On the experimental side, however, the available information is rather scarce. The appealing feature of giant resonance studies in unstable nuclei is that bulk properties of proton-neutron asymmetric nuclear matter can be studied. For example, the thickness of neutron skins can be derived from the excitation of the isovector giant dipole resonance by isoscalar probes (e.g. inelastic α scattering) and from the excitation of the isovector spin-dipole resonance in charge-exchange reactions. Such measurements have recently been performed, although only in stable nuclei only. Some of the new features predicted to occur in very neutron-rich nuclei are illustrated (see box “Giant Resonances and Exotic Nuclei”). An approach to study giant resonances using secondary beams of unstable nuclei was, until now, hampered by low luminosities and the lack of appropriate instrumentation. At present, only the dipole strength distribution can essentially be mapped, by utilising virtual photon absorption or virtual photon scattering in heavy-ion Coulomb excitation of unstable nuclear beams at intermediate to high energies. This can be done even at low beam intensities, as was proven in pioneering experiments at GSI and MSU.

Giant resonances are of paramount important for nuclear astrophysics. Often, relevant reaction rates under astrophysical conditions are dominated by giant-resonance contributions, frequently in unstable nuclei. For instance, neutron-rich nuclei with loosely bound valence neutrons may exhibit very strong (γ,n) strength components near particle threshold and thus, in turn, enhanced neutron-capture rates. Reactions mediated by the weak interaction also play a decisive role in many astrophysical scenarios. Prominent examples are electron capture and β-decay, both processes governed by Gamow-Teller (and Fermi) transitions. Implementation of new probes such as (d,^{2}He) and (^{3}He,t) facilitates the determination of these reaction rates. Magnetic resonances also govern neutrino-induced reaction rates on nuclei, e.g. those relevant in certain r-process scenarios. Large-scale shell model calculations in hand with high-quality data, e.g. from (^{3}He,t),(d,^{2}He), ($\vec{p},\vec{p}'$) and (e,e’) experiments which have become feasible recently, should provide reliable nuclear-structure input.

The next-generation radioactive ion-beam facilities will allow unprecedented measurements due to the implementation, in particular, of the standard tools in giant-resonance studies, i.e., inelastic electron scattering and scattering on light nuclei (p, d, ^{4}He,..). Promising experimental schemes in that respect, involving storage-cooler rings and intersecting electron colliders, are envisaged in new projects at RIKEN and GSI.

6.4 Instrumentation and facilities: current status and developments

6.4.1 Instrumentation and facilities

The continuous development of beams and instrumentation has been crucial for nuclear-structure studies. Whenever innovative experimental techniques for accelerating and/or detecting particles and radiation have been developed, new and quite often unexpected features have shown up. In that respect, it is of utmost importance to invest in new experimental ideas and technologies in order to expose nuclei to external probes and study their response under extreme conditions, i.e., by heating the nucleus (temperature degree of freedom), by bringing angular momentum to the nucleus (rapidly rotating nuclei), by forming very proton- or neutron-rich nuclei (approaching and mapping the drip-line regions) etc. It is developments such as these which have led to the experimental findings that have guided the field. Many of them are the result of studies with stable isotope beams and, the continuing importance of these facilities to the field must not be overlooked. Indeed, a new heavy ion-beam facility with at least one order of magnitude higher intensity than previously available would be of particular value, for example to facilitate the continuation of the SHE programmeme or in the study of very proton-rich nuclei produced by cold-fusion reactions.

Nevertheless, despite the many achievements and continuing requirement for stable isotope beam facilities, the discussion in the previous sections indicates that the major future developments centre on the production of energetic radioactive ion beams. Over the last decade our research community has undertaken the development, implementation and exploitation of the necessary new techniques, resulting in the commissioning of first generation radioactive ion beam facilities and the upgrade of existing facilities. The In-Flight facilities in Europe at GANIL and GSI, together with their counterparts at RIKEN, Japan, and MSU, USA, developed methods for extracting significant nuclear-structure information from scattering experiments with intermediate-to-high energy secondary beams of unstable nuclei, although restricted to nuclear masses up to A $\approx$ 50. In Europe as well, after the pioneering efforts in Louvain-la-Neuve in post-accelerating ISOL beams, two new ISOL-based RIB facilities have produced their first results (see box "First Results from SPIRAL and REX-ISOLDE") and the Munich project (MAFF) is under construction. Together with the facilities at Triumf, Canada, and Oak-Ridge, USA, these accelerator centers will form the basis of radioactive ion-beam research in the short term future.

The community is preparing for the next generation of radioactive beam facilities and instrumentation. From an experimental point of view, a "figure of merit" can be defined as consisting of three parts:

- **Intensity**: related to the secondary beam intensity.
- **Selectivity**: related to the purity of the secondary beam as well as to the resolving power of the experimental equipment.
- **Sensitivity**: related to the efficiency of the detection systems and their ability to deliver complete experimental information.

An increase in this "figure of merit" by several orders of magnitude is aimed for. This will involve a large number of technological challenges most of which have been identified and for certain cases major R&D work is needed to find suitable solutions. Also, dedicated set-ups at accelerators available for extended beam-time periods at specific and difficult experiments that represent a breakthrough in nuclear-structure research are needed.

6.4.2 Production of radioactive ion beams

Beams of exotic nuclei can be produced in two complementary ways: the ISOL method and the In-Flight separation method (see NuPECC report on Radioactive Nuclear Beam Facilities 2000).

The ISOL method produces unstable nuclei in reactions such as spallation, fusion evaporation, fission or fragmentation reactions induced by neutrons, protons, heavy ions, electrons or γ. The reaction products are stopped in a thick target that is kept at a high temperature to allow the radioactive isotopes to diffuse out of the target matrix and towards the ion source. After ionisation, the ions are extracted, modestly accelerated (typically to an energy of about 50 keV) and mass separated. In certain cases this low-energy ion beam is, after cooling and charge-state breeding, further accelerated for reaction studies.

The In-Flight method relies on heavy-ion fusion evaporation, fragmentation or fission reactions on relatively thin targets. Due to the reaction kinematics, the secondary reaction products leave the target at a velocity predetermined by the primary beam thus further acceleration is not required. The secondary beams are purified in an in-flight separator using electric and magnetic fields. In some cases the specific energy loss difference (dE/dx) for the different elements is used for further separation. Depending on the experimental requirements, the ion beam can subsequently be injected into a storage ring.

Substantial R&D work has to be accomplished in view of the next generation radioactive beam facilities such as the "International Accelerator Facility for Beams of Ions and Antiprotons" (at GSI) and the "European Isotope Separator On Line" (EURISOL). Here, only the major tasks only are itemised:

- High-intensity driver accelerators are the essential pre-requisite for reaching out far into the yet unexplored territories of exotic nuclei. Future In-Flight facilities, linacs (EURISOL, RIA), multi-stage cyclotrons (RIKEN) and synchrotrons (GSI) are under consideration. Aside from intensity, the driver concept needs to be concerned with aspects such as beam energy, quality and time structure, all of which are important for the secondary-beam experiments. The GSI concept relies on a double-ring synchrotron providing beams of exotic nuclei up to about 1.5

GeV/u in quasi-continuous or alternatively in pulsed mode operation. The later is essential for an efficient injection into the storage-cooler ring system allowing new types of experiments.

The EURISOL scheme is based on a 1 GeV, 4 MW, continuous-wave proton linac. Using the full power of the proton beam, very high fluxes of neutrons will be produced in a spallation target which in turn will induce fission of uranium. Part of the proton beam can also be directed onto a heavy target producing large quantities of (mostly) proton-rich exotic nuclei. The secondary beams will be post accelerated to a wide range of energies: from a few tens of keV up to about 10 MeV/A, and for masses ≤ 100 to about 100 MeV/A.

- Different scenarios for high-power production targets are being developed including proton-to-neutron converters in case of ISOL or thin targets sustaining the extreme peak power in pulse mode operation for storage ring applications. These studies need to include the important subject of radioactive waste handling.

- For the new RIB facilities at GANIL and ISOLDE, charge-state breeders based on Electron Cyclotron Resonance (ECR) and Electron Beam Ion Sources (EBIS) have been constructed. Their performances should be explored to plan the way for the second-generation facilities. Scenarios for efficient 1^+ charge state acceleration should be investigated. As experiments depend strongly on the quality of the delivered species R&D programmes were initiated and have achieved some impressive successes. High-quality, cooled beams can now be made available through RF coolers and Penning traps. In combination with laser ionisation, beams of high purity are produced a crucial factor when going towards the drip lines. Investigating and overcoming the present limitations should be pursued.

- Fragment separators of near 100 % acceptance are needed; a particular challenge in the case of secondary beams produced by in-flight fission of a primary uranium beam. Due to the fission kinematics, large apertures are required and the technical solution presumably involves super-conducting magnetic structures. In the case of in-flight separation, high primary beam energies, around 1 GeV/u, avoid multiple atomic charge states and thus provide optimal conditions for beam transmission and purification.

- The development of storage rings with sub-second cooling times to explore the shortest-lived nuclei has to be considered. This cooling time is presently the limiting factor in the ability of storage rings to reach such nuclei. Stochastic pre-cooling combined with electron cooling in separate rings, as envisaged in the accelarator concept at GSI, may provide a solution.

- A new route towards combining the benefits of the ISOL (e.g. good beam quality) and In-Flight techniques (e.g. short delay times) will be explored using a large gas cell coupled to a fragment separator as proposed for RIA. Fragments are stopped after range bunching in the gas cell and are then guided towards the exit hole using RF and DC electric fields. After extraction, the beam will be cooled using gas filled RF structures and prepared for further acceleration or deceleration. This method offers significant potential and its feasibility should therefore be tested and initial explorative experiments performed.

Finally, the availability of parallel multiple beams in order to perform a number of different experiments at the same time should be incorporated in every new facility. The planned experiments will become more and more complex and require a substantial increase in the amount of beam-time. This demand can only be met if sufficient access to parallel beams is provided.

6.4.3 Instrumentation

The existing instrumentation should be further improved and optimised. At in-flight separators recoil proton- or α-decay tagging has been optimised and proven to be very efficient at extracting information on nuclei produced in extremely weak reaction channels. So far, this was mostly combined with γ-ray arrays but recently, efficient electron detectors for conversion-electron spectroscopy have been included producing some tantalising results. Using these techniques, excited states of, for example, proton-unstable nuclei, extremely neutron-deficient nuclei along the Z=82 closed shell and SHE have been identified (see e.g. box "Super-Heavy Elements"). As a next step, compact multi-purpose focal-plane detection systems that allow tagging on different kinds of radiation (like protons, α's, electrons, β's and γ's) aimed at studying the decay of extremely short-lived isomers and ground states (for example the GREAT array) are being developed. The advancement of broad range, large acceptance, ray-tracing spectrometers is another essential requirement for this endeavor.

The field of γ-ray spectroscopy stands at the verge of a major breakthrough with the development of electronically segmented germanium detectors and digitised electronics. First results with the MINIBALL and EXOGAM detectors in Europe and other arrays elsewhere have shown very promising results. Ultimately these developments will lead to γ-ray tracking that increases the sensitivity of this technique by at least one order of magnitude. Projects like the AGATA array are moving in this direction.

Experiments with unstable nuclei stored in high-energy rings will provide a new class of nuclear-structure data. Due to luminosity constraints, so far essentially only non-destructive techniques have been applied to stored beams of exotic nuclei which are useful in mass and lifetime measurements. Given a drastic increase in beam intensity, stored radioactive ions could be utilised in scattering experiments. The benefits would be two-fold: elastic and inelastic scattering and charge-exchange reactions on light (polarised) internal targets (H, He,..) in inverse kinematics would allow us to probe the nucleus matter distribution and to induce selectively spin-isospin excitations. Combining a heavy-ion storage ring with an intersecting electron ring, opens up the wide field of scattering experiments with purely electromagnetic probes. Efficient and fast cooling forms the mandatory prerequisit for these new classes of measurements.

A new idea combining a low-energy muon and antiproton trapping facility with intense second-generation radioactive ion beams has recently been suggested to explore the possibilities of new exotic probes such as muonic and antiprotonic radioactive atoms i.e. a radioactive system which contains an antiproton or a negative muon in their atomic shell. In this way, unique information on the structure of exotic nuclei can be obtained. These very challenging ideas should be considered very carefully and their feasibility explored.

6.5 Opportunities and outlook

The study of the atomic nucleus has witnessed several major developments over the last decade. We have gained new insight into the dynamics of atomic nuclei but unresolved problems remain and new ones have emerged. The development of new theoretical tools, the growing computing capabilities, the pioneering work in radioactive-beam production and the ingenious developments in instrumentation give us confidence that, during the next decades, nuclear-structure research will flourish and yield surprises. The study of exotic nuclei in particular will shed light on new aspects of nucleonic matter and promises a much more comprehensive understanding of strongly-interacting many-body systems in general. This research evolves more and more towards international large-scale facilities but, many experiments and important parts of the R&D-work are carried out by university-based groups. The support of these groups including their local infrastructure is therefore absolutely essential for the success of the future large-scale projects.

Based on the evolution in our theoretical understanding of the atomic nucleus and on the development of experimental tools, we formulate the following main priorities.

- *Vigorous exploitation of the existing accelerators and instrumentation*

The competitive stable isotope beam and radioactive ion-beam facilities as well as instrumentation should be fully exploited since, in addition to the extracted physics results, major beam production and detector R&D can be performed. These facilities will deliver the experimental capabilities in the coming 5 to 10 years and will serve as important training sites. Parallel to this, strong support should be given to university-based nuclear-physics groups that are working at the frontiers of nuclear-structure research.

- *Full support for the new GSI accelerator complex and the EURISOL project*

  Nuclear-structure research needs both, In-Flight and ISOL type facilities, due to the obvious complementary nature of both techniques. Highest priority should be assigned to the realization of the proposed international accelerator complex at GSI including its instrumentation. The high-intensity In-Flight radioactive beam facility incorporated into this project is based on solid foundations formed from experience with the already existing In-Flight facilities operated at GSI and elsewhere. Intensities of secondary beams of exotic nuclei will increase by orders-of-magnitude and, the multi-storage ring concept offers experimental opportunities that are unique worldwide. In any case, the project is highly competitive in regard of corresponding efforts in Japan and USA. Under technological aspects, there are a number of challenging issues but the overall concept appears to be already very established. The ISOL-based facilities have produced their first results and have convincingly been shown to work. Still, substantial R&D work is needed for EURISOL, the European ISOL-based RIB facility. Bridging the gap between now and the commissioning of EURISOL goes hand in hand with the necessary R&D work. Therefore, the planned projects aimed at improving the existing RIB and experiments in Europe, involving accelerator, target and instrumentation developments (like, e.g., AGATA, MAFF, SPES, SPIRAL-II and REX-ISOLDE) should be strongly supported. A conceptual design study as well as siting for the EURISOL project should be made. For both facilities (GSI and EURISOL) the multi-user aspect should be fully incorporated in order to meet the anticipated beam-time demand.

- *Very strong support for rebuilding nuclear-structure and nuclear-reaction theory efforts*

  It has been recognized that in recent years not enough attention has been paid to maintaining the expertise and activity in nuclear-structure and reaction theory. The current situation requires vigorous and instant action to ensure that the physics goals presented in the LRP can be realized. We recommend that provisions for constructing new experimental facilities should guarantee an appropriate part for theory development, and that expansion of local theoretical groups should be encouraged. The very positive role played in nuclear theory by the ECT* centre in Trento is recognized and acknowledged, and the support for this centre should be maintained and expanded.

- *Communicate the highlights to society*

  The number of physics students and science students in general is in decline. Widespread communication and explanation of the numerous impressive results obtained in our field to the general public can be considered as an important step in raising the public awareness of, and level of interest in, nuclear physics and, indeed, in physics in general. The nuclear-physics community should continue to support this activity. The realization of larger-scale facilities and their physics opportunities as suggested above ensure the intellectual challenges needed to attract and motivate young and brilliant students.

7. Nuclei in the Universe

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P. Corvisiero (Italy), D. Frekers (Germany), S. Goriely (Belgium),
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7.1 Introduction

This report summarizes some recent highlights and the present status of nuclear astrophysics and evaluates its future prospects and needs. Nuclear astrophysics has developed in the last twenty years into one of the most important subfields of ‘applied’ nuclear physics. It is a truly interdisciplinary field, concentrating on primordial and stellar nucleosynthesis, stellar evolution, and the interpretation of cataclysmic stellar events like novae and supernovae. It combines astronomical observation and astrophysical modelling with meteoritic anomaly research and with nuclear physics measurements and theory. In fact, it is this broad scope which fascinates research in nuclear astrophysics and motivates many young researchers to start a career in this field.

The field has been tremendously stimulated by recent developments in laboratory and observational techniques. The rapid increase in satellite observations of intense galactic gamma-sources, observation and analysis of isotopic and elemental abundances in deep convective Red Giant and Asymptotic Giant Branch (AGB) stars, and abundance and dynamical studies of nova ejecta and supernova remnants allow the placement of stringent limits on the various stellar and nucleosynthesis models. Also, the latest developments in modelling stars, novae, X-ray bursts, and supernovae allow now much better predictions from nucleosynthesis calculations to be compared with the observational data. New spectroscopic capabilities have become available on the Hubble Space Telescope, and through new large telescope facilities like the VLT and the Keck. Highlights with significant public attention were the high redshift supernova search and its implication for the structure and dynamics of the Universe as well as the proof of oscillations for solar neutrinos on their way from the solar core to earth by earthbound detectors.

This solution to the solar neutrino puzzle does not only open the door to new physics beyond the standard model of particle physics, it also confirms the predictions of the solar models including their nuclear physics input. The latter included the measurement of the ^{3}He(^{3}He,2p)^{4}He reaction cross sections at the Gran Sasso low-energy underground facility. This milestone of nuclear astrophysics constitutes the first direct measurement of a reaction rate at stellar energies. Other highlights of experimental nuclear astrophysics include the development and successful use of novel neutron-time-of-flight facilities at Los Alamos and CERN, which allow to determine neutron capture cross sections for the s-process with unprecedented precision, the high-accuracy mass measurements of many unstable nuclei at GSI, ISOLDE and GANIL, the determination of more than 30 new half-lives for neutron-rich nuclei on the r-process path, and the precision measurements of spin-isospin responses in nuclei at KVI Groningen and Osaka, which are important inputs in supernova simulations and for supernova neutrino detectors. A new era of nuclear astrophysics has started with the use of radioactive ion-beam accelerators dedicated to the measurement of astrophysically relevant nuclear reactions involving short-lived nuclides. This field has been pioneered by the Louvain-la-Neuve facility, at which in the last 10 years several important low-energy nuclear reactions for explosive astrophysical environments have been studied. New installations are now operational at Louvain-la-Neuve, TRIUMF, GANIL and at CERN. They will allow to determine some of the most important reaction rates for the nuclear networks in novae and X-ray bursters. The next generation of radioactive ion-beam facilities, planned and proposed in Europe (GSI and EURISOL), in Japan and in the USA, will then allow to produce and experiment with most of the astrophysically important short-lived nuclides, promising to remove the most crucial ambiguities in nuclear astrophysics arising from nuclear physics input.

In many of the astrophysical models, nuclear theory has to bridge the gap between experimental data and astrophysical applications. Here, we clearly stand at the eve of a new era as the required step can now be taken on the basis of first-principle theoretical models rather than by empirical parametrization of the data. This should reduce the uncertainties connected with the extrapolations into yet unexplored parts of the nuclear chart in the near future, thus going timely hand-in-hand with the experimental developments.

Nuclear astrophysics has benefitted enormously from the progress in astronomical observation, astrophysical modelling and nuclear physics. But many fundamental open questions remain. Given the unique interdisciplinary nature of the field, a global understanding can only be achieved by combined and coordinated efforts in the three subfields. Clearly, nuclear physics plays a central role in this endeavour. It is the aim of this manuscript to identify the needs and prospects of experimental and theoretical nuclear astrophysics for the next 5 years. To underline the interdisciplinary character and the supplementing role of astrophysics and nuclear physics we first identify current and future developments of astrophysical observation and modelling, which will stimulate the nuclear physics programme, but also benefit from it. This programme is then individually described in the major subfields of nuclear astrophysics and the future prospectives and needs are derived.

7.2 Stellar physics and nuclear astrophysics

7.2.1 Stellar physics

Over the last decades, stellar physics has evolved into a field of research that uses high-precision data obtained by new generations of ground-based and space telescopes in all wavelength bands. Another basic ingredient is provided by nuclear data and detailed numerical models to study fundamental physics problems under conditions not reachable in laboratory experiments. These include the properties of neutrinos, the origin and abundances of the chemical elements, and the evolution of galaxies and of the Universe as a whole.

Structure and evolution of stars. Stars are an important component of the Universe and a major source of information about its structure and history. Due to much improved telescopes and their instrumentation, stellar properties can be measured with ever increasing precision. These advances are accompanied and completed by realistic stellar models. One example is the highly accurate solar model produced independently by several groups. Helioseismology allows to measure the sound velocity as a function of radial position, and thus the temperature and density, to better than 1% through most of the sun's interior. The new "Standard Solar Model", constructed on the basis of standard physics input (equation of state, nuclear reactions and initial composition, opacities, mixing-length theory of convection, etc.), reproduces the results of helioseismology extremely well. The recent confirmation of neutrino flavour oscillations by the Sudbury Neutrino Observatory SNO, making use of the sun as a well-calibrated neutrino source, is a major break-through in our basic understanding of neutrino physics.

EDDINGTON, an ESA mission to be launched in 2007, will allow to extend high precision stellar oscillation measurements to many stars in our cosmic neighborhood and to put the theory of stellar structure and evolution on a much improved empirical basis. Some of the nuclear reaction rates needed for the stellar models still carry significant uncertainties which certainly should be removed in the future.

Nuclear abundances in stars. With the increasing quality of stellar atmosphere models and the use of new telescopes and spectrographs, detailed abundance determinations in individual stars have become an important constraint in nuclear astrophysics. An outstanding example are the elemental (and some times even isotopic) abundances observed in many (ultra-) metal-poor giant stars. Here one avoids the complicated problem of chemical evolution and infers constraints on nucleosynthesis sites from the observed abundances in very old stars since their abundances have been polluted by only one or at most a few supernovae. Because of their low heavy element content, in particular iron, it is relatively easy to detect un-blended spectral lines of elements with mass-numbers exceeding even 50 in those stars.

It has been found that a certain class of very metal-poor stars with iron abundances of only about 10^{-3} of the sun contains no s-process material, but the r-process nuclei are sometimes over-abundant in these stars by up to a factor of 50 (relative to iron). Even more surprising, in all these cases the heavy r-process nuclei with $A > 130$ follow almost exactly the solar system pattern. On the other hand, the overall elemental abundances in these stars appear to be non-solar, even for the main components such as the CNO-group and α-capture elements.

Stellar diagnostics and extragalactic stellar astronomy In the current era of 8 and 10 meter-class telescopes, it has become possible to apply precise stellar diagnostics also to external galaxies. Recently new tools have been established to study the chemical evolution of galaxies and, in addition, provide promising new extragalactic distance indicators. In the coming years, high-resolution spectroscopy and imaging photometry by space-based telescopes will expand the astronomical data base even further in all wavelength bands. ESA's infrared satellite HERSCHEL has the potential of discovering the earliest epoch of proto-galaxies. Its main science objectives emphasize the formation of stars and galaxies, and the interrelation between them, but also include the physics of the interstellar medium and astrochemistry. NGST, the follow-up mission of HUBBLE, will shed light on the "Dark Ages of the Universe" by observing infrared light from the first generations of stars and galaxies. XMM-Newton, already in orbit, and XEUS, with a possible launch in 2015, will give X-ray data of similar quality.

Again, the basic building blocks for interpreting these data are stars and the gas in between them. These observations will shed light on the evolution of the chemical elements over the past 12 billion years in an unprecedented way, delivering the benchmarks nucleosynthesis models will have to match.

7.2.2 Late Stages of Stellar Evolution and Neutrino Astrophysics

For several decades, these branches of astrophysics have been very successful areas of research. Highlights include the construction of realistic models of thermonuclear and core-collapse supernovae, detailed investigations of nuclear burning in exploding stars, and the computation of nuclear abundances of the ejecta, including those of neutron-rich r-process isotopes of the heavy elements.

This progress was driven by advances in nuclear physics (weak and strong interaction rates, nuclear equation of state, neutrino processes), high performance scientific computing (2- and 3-dimensional hydro- and magneto-hydrodynamics, neutrino and radiation transport) advanced by the development of new numerical tools and the increasing power of modern super-computers and, of course, by new observational facts, discovered by large ground-based telescopes and space missions, such as Compton GRO, Chandra and XMM Newton, and the Hubble Space Telescope. A few outstanding examples are reviewed in the following subsections.

Core-collapse supernovae and nucleosynthesis Despite considerable progress, the

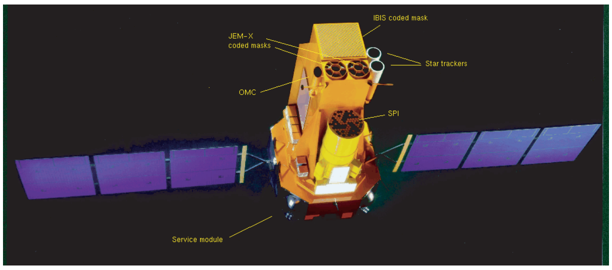

Figure 7.1: Artist impression of the INTEGRAL satellite. It combines unprecedented angular resolution (12 arcmin with the imager IBIS) and energy resolution (2.3 keV at 1.3 MeV with the spectrometer SPI) for gamma-ray astronomy. Among the scientific objectives are the galactic distribution of radioactive isotopes synthesized in stars, novae and supernova explosions and γ-rays from cosmic-ray interactions. (Courtesy of ESA/INTEGRAL)

physics of core-collapse supernovae and their nucleosynthesis remains to be an active field of research. Still open questions related to the debated explosion mechanism include the interaction cross sections of neutrinos in dense nuclear matter and the necessity to develop new methods to calculate their transport. However, some confirmation of the general picture is supplied by the detection of γ-ray lines of a few radioactive isotopes in supernovae, supernova remnants and the distribution of ^{26}Al in the disk of our Milky Way galaxy.

The field will certainly profit from the next generation of γ-ray instruments and in particular INTEGRAL, launched on October 17, 2002 (Figure 7.1). They will provide information about in-situ abundances of radioactive isotopes in explosive nucleosynthesis events and, thus, about the physical conditions in their deep interiors. The next generation of gravitational wave experiments either on ground (LIGO II, EURO, VIRGO) or in space (LISA) may allow us to map the dynamics of a star collapsing to a neutron star or a black hole.

γ-ray bursts Neutrinos and dense nuclear matter also play an important role in mergers of two neutron stars and of a neutron star and a black hole. In these events, dense nuclear matter is heated to tens of MeV and most of this energy is emitted in form of weakly interacting particles. It is believed that the annihilation of neutrinos into e^+e^- pairs may give rise to γ-ray bursts and may explain the "weak" subclass of the observed bursts. Of course, state-of-the-art simulations of such mergers have to be done in three spatial dimensions with all the relevant micro-physics and General Relativity included. Similarly, the collapse of rotating extremely massive stars to black holes, thought to be the cause of the class of very energetic γ-ray bursts, requires the same kind of micro-physics.

Here a combination of optical observations of γ-ray burst after-glows, carried out by robotic telescopes, X- and γ-ray observations with space-based telescopes, gravitational wave and, possibly, neutrino detections may allow us to better understand these most powerful explosions in the Universe.

Thermonuclear flashes and explosions The most interesting applications of explosive thermonuclear burning in binary stars are novae, X-ray bursts, and (type Ia) supernovae. For both, novae and X-ray bursts, the fusing matter tends to be proton-rich, many of the nuclei involved are unstable, and their reaction rates, which drive the burning, are not or only poorly known. The combined efforts of new X-ray telescopes in orbit, radioactive ion-beam facilities, which will allow to determine reliable reaction rates of short-lived proton-rich nuclei, and improved numerical models certainly will lead to major break-throughs.

For type Ia supernovae, the main question is how a thermonuclear burning front, which fuses carbon and oxygen mostly into ^{56}Ni, propagates in the degenerate matter of a massive white dwarf. As far as nuclear reactions are concerned, type Ia supernovae are fairly well understood, with the exception of certain weak rates which, however, have little impact on the explosion physics, but affect the elemental abundances of the ejecta. However, these supernovae have attracted considerable interest since they are thought to be good tools to measure cosmological parameters. Observations of this particular class of supernovae at high redshift seem to indicate that the expansion of the Universe is accelerating, possibly due to a positive cosmological constant or a new form of "dark" energy.

Neutron stars Neutron stars are unique "cosmic laboratories" in which our theories of dense nuclear matter at densities exceeding 10^{15} g/cm^3 are used to construct stellar models and can then be confronted with astronomical observations. Recently launched X-ray and gamma-ray observatories, such as RXTE-Rossi, AXAF-Chandra, and XMM-Newton have led to many remarkable discoveries: the kHz oscillations in low-mass X-ray binaries, numerous neutron stars in the type II supernova remnants, precise spectra of the surface radiation of solitary and binary neutron stars, and bursting millisecond pulsars. The number of observed neutron stars will soon reach two thousand. Still, this is a tiny fraction of the 10^8 neutron stars expected to exist in our Galaxy.

Precise mass determinations of neutron stars in binary systems are known since several years, the most famous being the Hulse-Taylor binary pulsar PSR 1913+16, for which the masses of both neutron stars are known to better than a few %. However, recent studies of the spectral and temporal properties of X-ray bursts observed from objects such as Cygnus X-2 with RXTE-Rossi allow for the first time to obtain also a reliable determination of the mass-radius relation of neutron stars. Similarly, masses and radii of nearby isolated X-ray sources such as RX J185635-3754 can be determined from their multi-wavelength spectral energy distribution. Finally, the near-constancy of the highest observed frequencies of the quasi-periodic oscillations of low-mass X-ray binaries, interpreted as being due to the orbital frequency of a marginally stable orbit, gives strong constraints on both masses and radii of their compact companions. All these observations and their interpretation will put our knowledge of the properties of neutron stars on a firm empirical basis.

Nuclear physics should try to explain the observed properties of neutron stars: this is our challenge. On the other hand, observations of neutron stars can be used to test and to constrain nuclear theory under extreme astrophysical conditions, which are far from the laboratory ones: these are our chances.

7.3 Hydrostatic burning

7.3.1 Nuclear processes during hydrostatic burning

Stars generate the energy, which allows them to stabilize and shine over lifetimes from millions to billions of years, by nuclear reactions in their interior. Simultaneously, the network of nuclear reactions operating in the hot, dense stellar interior is believed to be the source of nuclides of mass $A \geq 12$. The fate and evolution of stars depend strongly on their mass at birth. Stars with masses less than $\sim 8M_\odot$ reach temperature and densities in the center which only suffice to ignite the first two hydrostatic burning stages, hydrogen and helium burning. Mainly because of their enormously shorter lifetimes, massive stars (with masses exceeding about 13 $M_\odot$) were, and are still, the most efficient breeders of the heaviest elements. After helium burning, these stars go through periods of carbon, neon, oxygen, and silicon burning in their central core, before the procession of nuclear core burning stages ceases, resulting in the collapse of the stellar core and the explosion of the star as a Type II supernova.

Obviously, the star for which the best and most detailed data exist is our sun. Thus, it is natural that our general understanding of stellar structure and evolution be checked in detail against solar observations. Historically an outstanding role has been played by the detection of the neutrinos, which are generated by the various hydrogen burning chains operating in the sun's interior, and the quest to understand why the observed flux of solar neutrinos is less than predicted by the standard solar model. The solution to this famous solar neutrino puzzle was delivered by the Sudbury Neutrino Observatory (SNO) which experimentally proved the existence of oscillations for solar neutrinos. Furthermore, the SNO measurements, together with the high-precision helioseismology data, confirm the predictions of the solar models and their nuclear physics inputs. This, however, does not mean that more precise determinations of the solar nuclear reaction rates are no longer needed. On the contrary, the aim is now to turn the sun into a calibrated neutrino source which allows us to convert the measured solar neutrino event rates into information about neutrino masses and mixing parameters. This requires an even more precise knowledge of the various nuclear reaction rates in the sun!

The determination of stellar fusion rates in terresterial laboratories is strongly hampered by the fact that stars, including our sun, burn their nuclear fuel at such low energies that the cross sections, due to the Coulomb repulsion of the two colliding nuclei, are extremely small. To measure such cross sections requires accelerators with very high intensities and a very efficient background suppression. Despite enormous experimental efforts in the last decades, a direct measurement of stellar cross sections has been nearly impossible, and data, obtained at higher energies than those needed in stars, have to be extrapolated down to the stellar energy range. Such a procedure can obviously have considerable uncertainties. To reduce these uncertainties or to circumvent the notorious extrapolation procedure at all, considerable efforts have been spent in recent years to push the experimental limits to lower and lower energies and, simultaneously, to develop new indirect approaches to determine the required rates at stellar energies.

The underground LUNA laboratory at the Gran Sasso is an extremely background free facility dedicated to the measurement of astrophysically important low-energy nuclear cross sections. As a milestone, it has been possible at LUNA with the original 50 kV accelerator to directly determine the rates of the ^{3}He(^{3}He,2p)^{4}He and d(p,γ)^{3}He reactions at those energies at which these reactions operate in the core of the sun (Figure 7.2). Following the recommendations of the last NuPECC report, a new 400 kV accelerator, which will be dedicated solely to the study of astrophysically important fusion reactions, has recently been installed.

LUNA will determine the fusion rates of key-reactions in quiescent stellar burning with significantly improved precision. A prominent example is the ^{3}He(^{4}He,γ)^{7}Be reaction rate which is directly proportional to the flux of the high-energy ^{8}B neutrinos from the sun and hence is essential for the analysis of the observed solar neutrino fluxes in terms of neutrino masses and mixing parameters. Detailed studies of many reactions of the NeNa and MgAl cycles, which operate during hydrogen burning in stars more massive than the sun, should be performed. In particular, a precision measurement of the ^{25}Mg(p,γ)^{26}Al cross section can contribute to the solution of the astrophysical origin of ^{26}Al. In the future, the installation of a high-current 5-MV accelerator in the LUNA laboratory is desired. Among other important reactions, such a machine would allow the precision measurement of the rates for the ^{13}C(α,n)^{16}O and ^{12}C(α,γ)^{16}O reactions, where the first is important for studies of s-process nucleosynthesis.

The fusion of ^{4}He and ^{12}C nuclei to ^{16}O is the most important nuclear reaction in the development of massive stars. It occurs during the helium burning stage of Red Giant stars and its reaction rate decisively influences the subsequent stellar evolution, including the core collapse and the supernova explosion. Furthermore, this rate determines the abundances of the two brickstones of life, carbon and oxygen, in the Universe. Despite enormous efforts and significant progress made in several laboratories around the world in measuring the relevant low-energy elastic and capture cross sections, the stellar ^{12}C(α,γ)^{16}O rate is still not known with the required accuracy of $\approx 20\%$. Further improved measurements are needed. Besides direct measurements with a future 5-MeV accelerator at LUNA down to energies of about 500 keV (which is still higher than the energy of 300 keV, at which this reaction burns most effectively in Red Giants), crucial information to reduce the uncertainty in the rates can come from measurements in inverse kinematics or via indirect techniques like Coulomb dissociation or using high-intensity photon sources. Here, a new experimental approach is already undertaken at the 4 MV Dynamitron tandem accelerator in Bochum using the European Recoil separator for Nuclear Astrophysics (ERNA). In this approach, the reaction is initiated in inverted kinematics, i.e. a ^{12}C ion beam is guided into a windowless ^{4}He

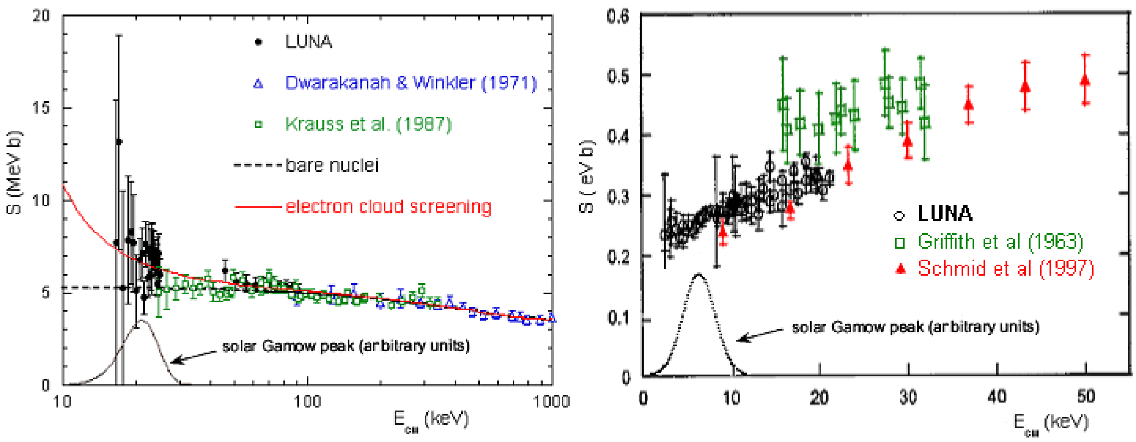

Figure 7.2: Reaction cross sections, expressed in terms of the astrophysical S-factor, for the ^{3}He(^{3}He,2p)^{4}He (right) and d(p,γ)^{3}He (left) reactions. It has been possible at the underground laboratory LUNA to directly measure these cross sections at solar energies (solar Gamow peak). (Bonetti *et al.*, PRL 82 (1999) 26)

gas target and the ^{16}O recoils are counted in a telescope placed in the beam line at the end of the separator.

The determination of low-energy cross sections from the observed reaction yield requires a precise knowledge of the effective beam energy. Energy loss effects in the target as well as screening effects of the target and projectile electrons (see below) on the reaction cross section have to be well under control. This is particularly important as such effects, if inaccurately corrected, will be amplified in the required extrapolation of the data to stellar energies. Recently, unexplained effects have been reported in the low-energy measurements of stopping powers and electron screening. It is important that these effects are confirmed and understood, requiring for example precision measurements of stopping powers at energies below the Bragg peak.

In recent years several indirect methods, which can avoid some of the apparent difficulties encountered in the direct approaches to determine astrophysically important low-energy cross sections, have been proposed and developed. In the Coulomb dissociation method, which can be viewed as the inverse of a capture reaction, a nucleus is dissociated by the virtual photons created in the strong Coulomb field of a heavy nucleus. Supplemented by considerable theoretical progress in modelling the 3-body process, Coulomb dissociation experiments have contributed to reduce the uncertainty in the solar ^{7}Be(p,γ)^{8}B fusion rate. Although this method can only provide partial information about the capture process; i.e. it can only determine the radiative capture cross section to the ground state of the compound nucleus, there are several astrophysically interesting reactions where this technique can provide valuable data, in particular if it can be applied to short-lived radioactive ion-beams.

For certain non-resonant radiative capture reactions, the capture process occurs at such large separations of the fusing particles that the reaction can be viewed as an external process which is solely determined by the asymptotic behavior of the nuclear wave functions in the initial scattering and in the final bound state. Then, the only unknown required to determine the astrophysically important low-energy cross section is the asymptotic normalization coefficient (ANC) of the final bound state, which can be indirectly determined in properly chosen peripheral transfer reactions. Such an approach, called the ANC method, has been recently developed and was successfully tested and applied to several astrophysically interesting reactions.

In the Trojan Horse (TH) method, originally developed at the LNS in Catania, an astrophysically relevant reaction a(A,B)b is studied via a three-body reaction x(A,Bb)c, in which the projectile x is well clustered into x=c+a. For appropriately chosen incident beam energies, the 3-body reaction can be viewed as a quasi-free break-up mechanism, in which the cluster c behaves like a spectator and does not affect the interaction between the fragments a+A. Under such conditions the desired a(A,B)b cross section can be deduced from the measured 3-body reaction yield. By properly balancing the Fermi motion of the cluster 'a' in the nucleus x with the incident beam energy, which can be chosen above the respective Coulomb barrier, the TH method is able to measure fusion cross sections at very low energies. Supplemented by important theoretical developments of the underlying 3-body reaction mechanism, the TH method has been successfully applied to the ^{6}Li(d,α) and ^{7}Li(p,α) reactions. One advantage of the TH approach is that it determines the cross section between bare nuclei and is, unlike direct measurements of the a(A,B)b reaction, not influenced by screening enhancements due to the presence of projectile and/or target electrons. The reported screening enhancement for most reactions studied so far are noticeably larger than theoretically expected. With its ability to measure the cross section for bare nuclei, the TH method can play a key-role in unravelling the disturbing difference between observed and expected electron screening effects. Clearly the clarification of this discrepancy needs more experimental and theoretical work. Such studies might also help to improve our understanding of electron screening effects in stellar plasma, which, once the proposed accurate measurements of nuclear cross sections are achieved, represent the largest uncertainties of the respective stellar rates.

7.3.2 The s-Process

The slow neutron-capture process (or s-process) synthesizes heavy elements by a sequence of neutron captures and β-decays, mainly processing material from seed nuclei below and near the iron peak into a wide range of nuclei extending up to Pb and Bi. As the involved neutron capture times are usually significantly longer than the competing β-decays, the s-process path runs along the valley of stability in the nuclear chart. This allows the laboratory determination of the involved neutron capture cross sections and half-lives, making the s-process the probably best understood nucleosynthesis network from a nuclear physics point of view.

However, the main uncertainties in s-process predictions are still associated with the presently favored stellar sites. According to our current understanding, two s-process components are needed to reproduce the observed abundances. The ^{22}Ne(α,n)^{25}Mg reaction, which occurs during helium core burning of CNO material in massive stars (heavier than $10M_\odot$), is believed to supply the neutrons for the weak component that produces the nuclides with $A < 90$. Helium-flashes followed by hydrogen mixing into the ^{12}C-enriched region in low and intermediate mass ($< 10M_\odot$) AGB stars are believed to be the site of the main s-process component that builds up the heavy elements up to the Pb and Bi range. As suggested by recent AGB models, which include diffusive overshoot and rotational effects, protons are partially mixed from the H-rich envelope into the C-rich layers during the third dredge-up and are then captured on ^{12}C, which provides the fuel for producing ^{13}C via ^{12}C(p,γ)^{13}N(β,ν)^{13}C. The subsequent ^{13}C(α,n)^{16}O reaction is considered to be the principal neutron source for the main s-process component. These models predict that low-metallicity ($Z \leq 0.002$) AGB stars should exhibit large overabundances of Pb and Bi as compared to other s-elements. The discovery of such 'lead stars' (very low-metallicity stars enriched in s-elements and characterized by a large Pb overabundance compared to any of the other s-elements Ba, La or Ce) has been reported very recently. This discovery may be the s-process "Rosetta stone" which validates the 'proton-mixing' scenario in AGB stars and also gives a clear indication that the s-process already took place early in the Galaxy.

Although the nature and extent of the convective processes as well as the low energy reaction cross section for ^{13}C(α,n) are largely unknown, our understanding of the nuclear mechanisms which are responsible for the production of the s-nuclei can be regarded as quite satisfactory, reflecting major experimental and theoretical efforts and progress in the last decade. As a highlight, a recent measurement has strongly reduced the uncertainties in the stellar $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ cross section. However, due to the importance of this reaction as a main neutron source, further effort via direct and indirect (e.g through (n,α) on ^{25}Mg) approaches is still desirable to reduce the remaining uncertainty.

S-process simulations require the knowledge of a large number of stellar neutron capture cross sections at typical energies of $10 \lesssim kT \lesssim 50$ keV on targets in the $12 \leq A \leq 210$ mass range. Much dedicated experimental work, in particular in university laboratories, has led to a substantial improvement in our knowledge of relevant (n,γ), (n,p) and (n,α) cross sections. In particular, the neutron capture cross section on the rarest stable nucleus in nature ^{180}Ta has recently been measured. Furthermore, it has experimentally been demonstrated that the short-lived ground and the long-lived isomeric state of ^{180}Ta can be equilibrated at stellar temperatures in excess of about 4 10^8 K, changing the effective half-life of ^{180}Ta by 15 orders of magnitude. These difficult experiments are of particular relevance to our understanding of the possible s-process contribution to the galactic ^{180}Ta enrichment.

However, some neutron capture cross sections, in particular those for unstable nuclei on the s-process path, are not yet determined with the required accuracy, especially at the energies of $kT \simeq 10$ keV relevant for the s-process in AGB stars. The new unique neutron time-of-flight facility at CERN with its high neutron fluxes is expected to strongly improve the experimental determination of radiative neutron capture cross sections. One of the first astrophysically relevant experiments at this facility will determine the capture cross section on the Os isotopes, which is of particular interest in the Re-Os cosmochronometry. A close investigation of neutron capture reactions on long-lived beta-unstable neutron-rich isotopes is particularly important, as these nuclei represent potential branching points in the reaction path. Detailed analysis of the observed s-process abundance distribution in conjunction with neutron capture and beta decay data on these branching point nuclei provide important information about the temperature, density, and neutron-flux conditions at the s-process site. Neutron capture measurements on branching point nuclei offer a unique tool for testing the stellar s-process models. The determination of the relevant beta-decay rates can, however, be much complicated by the fact that thermally excited nuclear states might change the stellar half-lives significantly. With the exception of isomeric states, the half-lives of excited states cannot easily be measured, and the complexity of the nuclear structure makes the prediction of the required β-decay matrix elements a real challenge for nuclear theory. A special β-decay mechanism, referred to as bound-state β-decay, can play an important role for ionized atoms, and significantly affect the production of some specific s-nuclides. The remarkable experimental observation of the bound-state β^- decay of the fully ionized ^{187}Re atom achieved at the GSI in Darmstadt has been an important step in the reduction of the uncertainties associated with the galactic Re-Os chronometry.

7.4 Supernovae and dense objects

Simulating core-collapse supernovae has been at the forefront in astrophysics for several decades and the general picture is now well developed. There is a consensus that neutrinos play an essential role in the supernova mechanism. Therefore the development and incorporation of multi-group (i.e. neutrinos of different flavors and energies) Boltzmann neutrino transport into the one-dimensional models has been a major recent achievement; a similar treatment in multi-dimensional collapse simulations, which currently consider neutrino transport rather crudely, is computationally extremely demanding. Despite significant progress, one-dimensional collapse simulations currently fail to explode. Does this imply that some of the microphysics ingredients of the models are incorrect and need improvement or do supernova explosions rely on three-dimensional effects such as convection or rotation? This fundamental question is still open. Much of the relevant micro-physics relates to weak-interaction processes in nuclei and nuclear matter under extreme conditions (density and temperature), but also uncertainties in the nuclear equation of state (EOS) might prove to be essential. The latter also plays a major role in the description of neutron stars, which are generally viewed as the laboratory for nuclear physics under extreme conditions. Progress in computer technology, the development of new and advanced many-body models and, probably most importantly, the new era of experimental facilities promise to reduce the nuclear-physics related uncertainties in supernova simulations and neutron star models.

7.4.1 Nuclear input for core-collapse simulations

After the formation of an iron core in its center, a massive star has run out of nuclear fuel to counteract gravity. The core starts to contract and becomes unstable against electron capture due to the associated increase in electron chemical potential. Electron captures cool the core, as neutrinos carry away energy, but also reduce the electron degeneracy pressure which counteracts the contraction. Both effects accelerate the collapse. Furthermore, the core composition is driven to more neutron-rich and heavier nuclei.

Under collapse conditions, electron captures are dominated by Gamow-Teller (GT) transitions. Relevant capture rates have been evaluated on the basis of shell model studies and experimental data, whereever available, for nuclei with $A = 45 - 112$. The results are quite distinct from the phenomenological input, which has conventionally been used in collapse simulations. The consequences for the presupernova and collapse models are significant. Interestingly, β-decays can compete with electron captures for a short period during silicon burning, adding an important cooling source.

Given the importance of weak-interaction processes during the collapse, a strong and dedicated experimental programme to test and give credibility to the new shell model calculations is therefore warranted. Experimentally, GT transitions can be studied using intermediate nucleon-nucleus scattering at low momentum transfers. In the GT_- direction (important for β decays) this goal has been achieved through (p,n) and (^{3}He,t) charge-exchange reactions. On the other hand, the determination of the $B(GT_+)$ strength, as required for electron captures, is considerably more difficult. The neutron beams, which were used in the pioneering (n,p) experiments at TRIUMF, were secondary beams produced through the ^{7}Li(p,n) reaction, and the typical resolutions obtained in these experiments were of the order of 1 MeV. More recently, secondary triton beams at sufficiently high energies have become available, which allow the study of GT_+ transitions rather competitively through the (t,^{3}He) reactions. Another and potentially even more powerful tool to explore the spin-isospin-flip transitions in the GT_+ direction is the (d,^{2}He) reaction. Here ^{2}He denotes a two-proton unbound state in the $^1S_0$(pp), T=1 channel. A major development step for (d,^{2}He) experiments was recently achieved by a group at the KVI Groningen who demonstrated that a resolution on the order of 150 keV can readily be obtained with their spectrometer equipment.

The equivalence of the (n,p) and the (d,^{2}He) reactions has been demonstrated by a detailed comparison with the (p,n) reaction on the self-conjugate nuclei ^{12}C and ^{24}Mg. The study of the (d,^{2}He) reaction for heavier nuclei, like those in the pf-shell, is now successfully underway (Figure 7.3). The present energy resolution of about 150 keV allows a rather detailed comparison with theory up to individual levels. An extensive experimental programme will not only supply direct information about specific GT_+ transitions and energies, which can be used in the electron capture rate evaluations, it will also detect possible shortcomings in the shell model residual interaction and hence indirectly improve the rate compilations. Needed data include GT strength distributions for odd-odd nuclei and odd-A odd-N nuclei. In the later stage of the collapse, the matter composition involves many nuclei with proton numbers $Z < 40$ and neutron numbers $N > 40$, for which GT_+ transitions in the independent particle model are completely blocked. Here it is essential to know how strongly thermal excitations and cor-

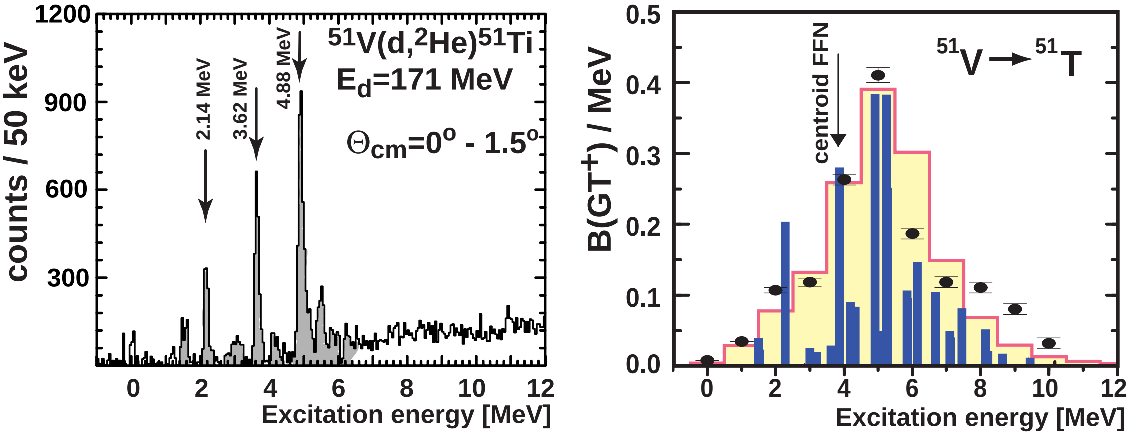

Figure 7.3: Spectrum of the reaction ^{51}V(d,^{2}He)^{51}Ti at 170 MeV incident energy measured at the AGOR cyclotron at the KVI in Groningen showing a number of strong GT transitions. The experimental resolution is 140 keV. The right part shows the results from TRIUMF using the (n,p) probe where the resolution was typically of order $1 - 1.5$ MeV (full points). The bars (not to scale) indicate the results of the shell model calculation, which, after folding with such resolution, yields the full curve. The experimental resolution in the (d,^{2}He) case (left part) now allows a highly detailed comparison with theoretical calculations. (Courtesy of C. Bäumer *et al.*

relations, which mix the (fp) and (gds) orbitals, provide an unblocking of the GT_+ strength. An experimental programme must be therefore extended into this mass range. Many unstable neutron-rich nuclei are quite abundant in the core, particular during the final collapse. To obtain these GT_+ data, requires the availability of radioactive ion-beams and charge-exchange experiments using inverse kinematics.

We mention that dedicated β decay measurements, also involving unstable nuclei, are important. For one, they can supply relevant information about low-lying transitions which are often decisive for the stellar weak-interaction rates at the onset of the collapse, and further, they deliver data against which charge-exchange measurements can be compared with or normalized to.

During the collapse, electron capture processes produce ν_e neutrinos in the energy range of MeV's to tens of MeV. The role neutrino-nucleus reactions play is not fully explored. While charged-current (ν_e, e^-) reactions are strongly Pauli-blocked due to the large electron chemical potential, inelastic neutrino-nucleus scattering may compete with inelastic neutrino-electron scattering as the energy-exchange mechanism to thermalize the neutrinos in the core. Reliable estimates of (ν, ν') cross sections, which can be enhanced significantly due to finite temperature, require the knowledge of the GT and first-forbidden isovector spin-dipole response, where the finite-temperature effects are mainly sensitive to the detailed distribution of the GT_0 strength. Systematic theoretical estimates for these reactions should be made and an experimental programme to test and improve the theoretical estimates is needed.

7.4.2 Weak-interaction processes in hot, dense matter

Neutron stars (NS) are formed in the center of massive stars during their supernova explosion. Here the matter temperature can exceed 10^{11} K, making the EOS of hot, dense matter and neutrino transport (opacities) crucial ingredients for NS births and supernova explosion models. Calculations of the EOS and neutrino opacities under such conditions have to be improved by using more realistic strong interactions, which, in particular, include the effects of tensor correlations among nucleons. If one considers that about 99 % of the energy released in the explosion is carried away by neutrinos and that only a tiny $\sim$ 1% fraction of this energy must be transferred by neutrino absorption on nucleons to matter behind the stalled shock wave to achieve a successful explosion, then it is quite obvious that neutrino transport in hot, dense matter is of paramount importance for reliable supernova models.

Weak interaction processes accompanied by neutrino emission are responsible for the cooling of neutron stars during the first 10^5 years of their life. An improved description of such processes, based on more realistic strong interactions and considering the in-medium renormalization of the weak interaction, is necessary. The effects of nucleon superfluidity on NS cooling should further be studied. Forthcoming observations of cooling neutron stars at known distance and age will be decisive for constraining the theoretical models. Also the discovery of young neutron stars of known age would be of great importance, as they can supply convincing arguments for the presence of non-standard neutrino-emission processes (direct Urca with nucleons, pion or kaon condensates, or maybe even quark matter) in neutron-star cores.

7.4.3 Neutron star models

Current models divide the interior of a neutron star into two regions - the crust and the core. The crust, forming the outer layer of ∼ 1 km thickness, contains atomic nuclei immersed in a dense electron gas, and, above the neutron-drip point at densities $\rho \sim 5 \times 10^{11}$ g/cm^3, also in a neutron gas. At the bottom of the crust the density reaches $\rho \sim 10^{14}$ g/cm^3, and only a few percent of nucleons are protons. Under the crust lies the liquid core. For nuclear densities around $\rho \sim 3 \times 10^{14}$ g/cm^3 it consists of a plasma of neutrons with a few percent admixture of protons and electrons. With increasing density, muons and hyperons are expected to appear in the matter. The central density of neutron stars can be as high as $(5-10)$ times nuclear densities. This makes theoretical models rather uncertain. Some of these models predict that the inner core of neutron stars consists of kaon or pion condensates, or even of quark matter. It will be one of the major challenges to test these predictions.

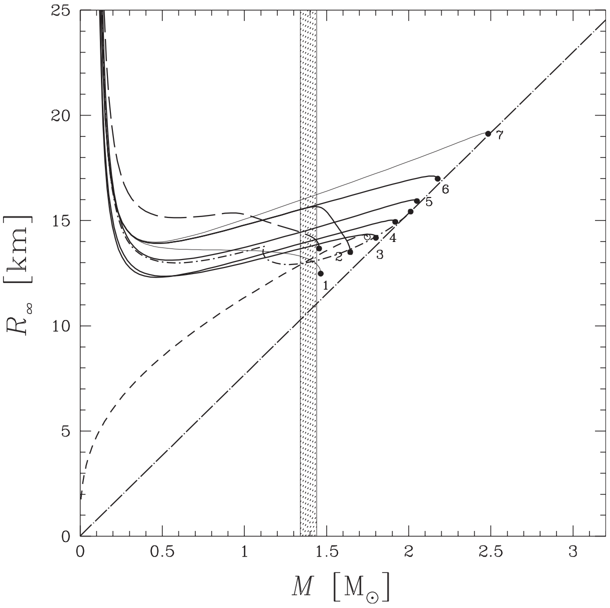

Figure 7.4: The so-called "radiation radius" (or "apparent radius") R_∞, as measured by a distant observer, versus the neutron star mass M, for several theoretical Equations of State of dense matter. The dashed strip corresponds to precisely measured masses of neutron stars. The long-dashed-dotted line is an absolute lower-bound on R_∞ at a given M which is a consequence of space-time curvature around the neutron star. The short-dashed line, which allows for very low values of R_∞, corresponds to strange (quark) stars. Notice that R_∞ cannot be smaller than 11 km for ordinary neutron stars. Sensational reports in April 2002 claimed that RX 185635-3754 has the apparent radius smaller than 8 km (and is therefore a low-mass quark star); however, this result was questioned later. (Courtesy of P. Haensel)

The outermost layer of a neutron star is called the outer crust. It is composed of neutron-rich nuclei immersed in a dense electron gas. These nuclei, which are beta-unstable in the laboratory, are stable in dense matter due to the Pauli-blocking of the final electron states by the degenerate electron gas. For matter densities $\rho < 10^{11}$ g/cm^3 the outer crust is expected to contain nuclei which can be studied in the laboratory. Of particular interest is the doubly-magic nucleus ^{78}Ni which is expected to be quite abundant at densities $\rho \simeq 10^{11}$ g/cm^3, found in the outer crust some 300 m below the neutron-star surface. Nuclei, present at higher densities (depth), have to be described by nuclear-mass formulae. More reliable mass formulae at

$Z/A \simeq 0.3$ are essential for the correct modelling of the bottom layers of the outer crust. The structure of the outer crust, and in particular its matter composition, is essential for the correct interpretation of surface temperature data of cooling neutron stars, obtained form X-ray observations.

The structure of the inner crust, in which very neutron-rich nuclei are immersed in a neutron gas, can only theoretically be studied. More reliable effective nuclear interactions as well as efficient and precise many-body simulations are needed to improve models of this part of the crust, which is important for the understanding of phenomena like the glitches in radio-pulsar timing. Particularly important here is the determination of the structure of the crust-core interface and of the interaction of superfluid neutrons with nuclei forming a crustal lattice. These two aspects are currently treated rather crudely in neutron star models. While the knowledge of the EOS of the crust is relatively good, the uncertainties in the actual crust composition (pure or heterogeneous), which depends sensitively on the kinetics of its formation, are still large.

The core of the neutron star is expected to contain some $95 - 98\%$ of its mass. The core EOS is essential for the neutron-star structure, and in particular for the determination of the maximum mass for neutron stars, $M_{\max}$; compact objects with $M > M_{\max}$ then have to be black holes. The knowledge of the core composition and the EOS above twice nuclear densities becomes increasingly worse with increasing density and is clearly insufficient at $(5 - 10)$ times nuclear densities. Up to now, the most reliable existing EOS of the core were derived assuming the simplest possible composition (neutrons, protons, electrons, muons) and using the best realistic nucleon-nucleon interactions supplemented with phenomenological three-body forces. These EOSs predict a maximum neutron star mass $M_{\max} = (1.9 - 2.2)\ M_{\odot}$. State-of-the-art many-body theories with the best existing N-N interactions should be implemented to narrow the ambiguities of the present EOSs, taking advantage of the impressive power of the forthcoming computing facilities. The role of the three-body and four-body forces as well as of relativistic effects in the many-body problem must be clarified. Studies of the impact of hyperons on the EOS should be continued, including the extension of the nucleon interactions to the hyperon sector. However, the progress is here to a large extent limited by poor experimental knowledge of the hyperon-nucleon and hyperon-hyperon interaction. The development of a reliable core EOS can benefit significantly from heavy-ion collision experiments, which probe the EOS of dense hadronic matter, albeit under different physical conditions than those in neutron star cores.

On the observational side, new determinations of NS masses in binary systems, and in particular more precise measurements of masses in the range $(1.6 - 2.0)\ M_{\odot}$ (measured in some X-ray binaries) could shed light on the actual value of $M_{\max}$ for neutron stars and would put severe constraints on the hyperon-nucleon interactions in dense matter, which are decisive for the thresholds at which hyperons appear in dense matter. The NS radius is very sensitive to the EOS. Calculations show a correlation of neutron star radii with neutron radii of heavy nuclei; precision measurements of such radii for lead isotopes might be quite helpful. The observational determination of NS radii has just begun, but holds great future potential. The measurement of radii of neutron stars with $M = (1.0{-}1.6)\ M_{\odot}$ will allow the determination of the EOS at two-three times nuclear densities, and puts severe constraints on the theory of nuclear matter at supranuclear densities (Figure 7.4). The neutron star structure is also important for the shape of gravitational waves emitted at the final stage of the coalescence of a neutron star - neutron star binary, which is considered as the most promising astrophysical source of gravitational radiation searched for by the gravitational-wave detectors which will become operational in this decade.

Different models predict the existence of quite exotic phases of dense matter in neutron stars (pion and kaon condensates, quark matter). Therefore experimental searches for the precursors of phase transitions in dense nuclear matter, as they might be produced in heavy-ion collisions, are of paramount importance. A possible candidate is the enhancement of the K^- yield observed in heavy-ion collisions at the GSI. Such experimental efforts have to be extended. Observational signatures for a phase transition in the NS core can be deduced from anomalies during spin-down or from abnormally small pulsation frequencies or radii. An interesting prospective is the possible existence of color superconductivity in high-density quark matter which could have profound implications for various NS properties. There is general concensus that the observation of a stellar "apparent radius" smaller than 11 km will be a reliable proof that strange quark stars built from deconfined self-bound quark matter exist (Figure 7.4). Further important constraints will come from experiments at the new GSI facility searching for the quark-gluon plasma and, in particular, for stable or metastable strange-matter.

7.5 Explosive burning

7.5.1 The p-process

It is now well accepted that the production of the stable neutron-deficient isotopes of the elements with charge number $Z \geq 34$ (classically referred to as the p-nuclei) occurs in the oxygen/neon layers of highly evolved massive stars during their presupernova phase or during their explosion. At the temperatures of about 2 to 3 billion degrees, which can be reached in those layers, the p-nuclei are synthesized by (γ,n) photodisintegrations of preexisting more neutron-rich species (especially s-nuclei), possibly followed by cascades of (γ,p) and/or (γ,α) reactions. It has also been proposed that those nuclear transformations could take place in the C-rich zone of Type Ia supernovae as well as in the envelope of exploding sub-Chandrasekhar mass white dwarfs on which He-rich material has been accreted. These alternative sites require improved explosion modelling to guarantee a reliable p-process seed abundance distribution.

The p-process is essentially a sequence of (γ,n), (γ,p) or (γ,α) photodisintegrations reactions, possibly complemented by captures of neutrons, protons or α-particles at energies typically far below 1 MeV or the Coulomb barrier in the case of charged particles. So far, relevant rate measurements, mainly involving radiative neutron and proton captures, are only available for stable targets. This data base covers not more than a minute fraction of the needs for p-process simulations. As the measurements are for the target ground state only, possible contributions of excited states to the stellar rates will have to be modelled. The available experimental data play an important role in the validation of the various nuclear ingredients entering theoretical predictions (see Section 7.7) and can also be used in estimates of reverse photonuclear rates.

Recent experiments have provided direct measurements of some (γ,n) reactions at the low energies of interest for the p-process, i.e close to the photodisintegration threshold. One of the techniques is based on the construction of a quasi-thermal photon spectrum from a superposition of bremsstrahlung spectra with different endpoint energies. As an alternative, the 'Laser Inverse Compton (LIC)' γ-ray source uses a real photon beam in the MeV region produced by head-on collisions of laser photons on relativistic electrons and produces quasi-monochromatic γ-rays in the energy range 1 to 40 MeV. An important advantage of the LIC γ-rays over the bremsstrahlung approach is their more intense peaking in the energy window of astrophysical interest in addition to their better quasi-monochromaticity. The bremsstrahlung and LIC techniques have been used so far to measure the rates of a few (γ,n) reactions. In particular, the latter experimental approach has provided cross sections to the ground and isomeric state for the $^{181}\mathrm{Ta}\,(\gamma\,,\mathrm{n})\,^{180}\mathrm{Ta}$ reaction, which is of special interest in p-process models. These measurements have to be complimented by the determination of the $^{180}\mathrm{Ta}^{\mathrm{m}}\,(\gamma\,,\mathrm{n})\,^{179}\mathrm{Ta}$ reaction rate. Another prime interest in p-process studies is the synthesis of the rare odd-odd p-nuclide ^{138}La. This requires the measurements of the $^{139}\mathrm{La}\,(\gamma\,,\mathrm{n})\,^{138}\mathrm{La}$ and $^{138}\mathrm{La}\,(\gamma\,,\mathrm{n})\,^{137}\mathrm{La}$ reaction rates. More generally, systematic measurements of the photoneutron cross sections at energies close to the neutron threshold will certainly reduce the remaining uncertainties in the stellar rates for the numerous isotopes involved in the p-process.

Experimental data for charged-particle induced reactions of p-process interest used to be scarce. This situation is largely due to the smallness of the related reaction cross sections at the sub-Coulomb energies of astrophysical interest. However, an important effort has recently been devoted to the measurement of a series of (p,γ) reaction cross sections on medium mass nuclei with $34 \leq Z \leq 51$ at low enough energies to be of astrophysical relevance. These experiments conducted principally at small facilities (Demokritos, Stuttgart) make use of two techniques, the activation method and the in-beam measurements. So far, data are available only for stable targets up to about Sb. A compilation of the present data, as well as an extension of the experimental efforts towards heavier ($Z > 50$) targets would be most valuable in order to better constrain and improve global reaction models (Section 7.7).

The (γ, α) reaction rates are usually determined from data on the reversed reactions. However, relevant (α, γ) data are very rare. A recent ${}^{144}\mathrm{Sm}\,(\alpha\,,\gamma)\,{}^{148}\mathrm{Gd}$ experiment is not only of astrophysics interest, but also a stringent test case for a reliable determination of the α-nucleus optical potentials at low energies. Indeed, all parametrizations failed to give a satisfactory description of the reaction cross section at the energies (around 10 MeV) of interest for the p-process. This measurement illustrated quite drastically the difficulties to reliably predict low-energy (α,γ) cross sections. New experimental data, especially for low-energy radiative captures on nuclei in the $A \simeq 100$ and $A \simeq 200$ mass range, are strongly required in order to further constrain the determination of a reliable global α potential. In this respect, low-energy elastic α-scattering, as well as captures of the (α,n), (n,α) or (α,p) types will also bring valuable information about the α-particle-nucleus interaction.

7.5.2 Nucleosynthesis in explosive Binary Systems

Thermonuclear explosions in accreting binary star systems have been an object of considerable attention. The basic concept of the explosion mechanism seems reasonably well understood, but there are still considerable discrepancies between the predicted observables and the actual observations. The proposed mechanism involves binary systems with one degenerate object, like white dwarfs or neutron stars, and is characterized by the revival of the dormant objects via mass overflow and accretion from the binary companion. The characteristic differences in the luminosity, time scale, and periodicity depend on the accretion rate and on the nature of the accreting object. Low accretion rates lead to a pile-up of unburned hydrogen, causing the ignition of hydrogen burning via pp-chains and CNO-cycles with pycnonuclear enhancements of the reactions after a critical mass layer is attained. On white dwarfs this triggers nova events, on neutron stars it results in X-ray bursts. High accretion rates above a critical limit cause high temperatures in the accreted envelope and less degenerate conditions, which result in stable hydrogen burning. Such high accretion conditions on white dwarfs cause supernova type Ia events. The observed relation between lightcurve and intrinsic brightness for nearby type-Ia supernovae makes them astronomical standard candles. In the last years an extended programme of observation of high-redshift supernovae led to the spectacular and surprising finding of an accelerated expansion of the Universe. Here, a better knowledge of the explosion mechanism is essential to confirm the brightness-lightcurve relation also for low metallicity SN. Type Ia supernovae are usually associated with a large amount of ^{56}Ni formation and, hence, are considered the main producers of iron elements in the Universe. Electron captures on the incinerated material, plus the neutron excess previously stored in the He-burning product ^{22}Ne, lead to the production of neutron-rich isotopes such as ^{48}Ca, ^{50}Ti, and ^{54}Cr. The final amount depends sensitively on the propagation speed of the burning front and the relevant electron capture rates, the latter being likely the most important nuclear physics input required in type Ia models.

Currently large uncertainties are associated with the modelling of accretion, explosion mechanism and burning front development and with the microscopic nuclear physics component of novae and X-ray bursts. The nuclear energy generation provides the observed luminosity of the event, the combination of rapid mixing, convection and far-off-stability nucleosynthesis is responsible for the observed abundances in the ejecta. Simulations of novae and X-ray bursts will noticeably benefit from post-accelerator facilities for radioactive ion-beams, which promise to remove the uncertainties of some of the key reactions involved in the respective nuclear networks.

Novae White dwarfs constitute the final phase of the evolution of low and intermediate mass stars. Their composition is mainly C, O or O, Ne, depending on the progenitor mass. Accretion of hydrogen-rich material from the envelope of a companion star and its mixing into the white dwarf matter leads to the onset of hydrogen burning under degenerate conditions. After accretion of a critical amount of matter, the hydrogen is burned explosively via the hot CNO, NeNa and MgAl cycles at high temperature ($T \leq 3.5 \cdot 10^8$K) and density ($\rho \approx 10^4$ g/cm^3). The burning products are ejected into the interstellar medium, where they can be detected by astronomical observations, which put important constraints on the models.

A principal interest in novae modelling focusses on the synthesis of the radioactive isotopes ^{7}Be, ^{18}F, ^{22}Na and ^{26}Al. The observation of the characteristic gamma-ray emission of these isotopes from a nearby nova is among the objectives of the European satellite INTEGRAL. Comparison of the observed *isotopic* yields with model results will give stringent constraints to some model parameters, and in particular on the still uncertain mixing process of the accreted hydrogen with the white dwarf material and the magnitude of the ejected mass. Nuclear astrophysics in Europe is especially well prepared to advance significantly in these questions with the availability of a state-of-the-art hydrodynamical nova code at Barcelona and the observational data expected from INTEGRAL. However, some important nuclear input to these models is still needed to achieve this goal, especially reaction cross sections involving unstable isotopes.

The nuclear reaction network in nova explosions extends up to mass $A \approx 35$ and includes proton capture reactions on several short-lived isotopes on the neutron-deficient side of the stability valley. The determination of the relevant cross sections has begun in some pioneering experiments at radioactive ion-beam facilites like ORNL, Argonne and Louvain-la-Neuve for the ^{18}F(p,α) reaction, which determines the final amount of ^{18}F synthesized in novae. This isotope is detectable in the first few hours after the explosion in the expanding shell of the ejected material by the characteristic e^+e^- annihilation radiation following its β-decay. Other important reactions for the synthesis of ^{22}Na and ^{26}Al include e.g. the short-lived isotopes ^{21}Na and ^{25}Al. The flow out of the MgAl-cycle to higher masses passes by several neutron-deficient P and S isotopes. For all these isotopes, including also some stable ones, proton capture cross sections at thermonuclear energies must be determined.

Much progress will certainly come in the near future from the availability of beams of these unstable isotopes at radioactive ion-beam facilities. Reaction cross sections at nova temperatures are generally very small and indirect approaches, like transfer reactions, ANC or the Trojan horse method will play an important role besides direct measurements to determine proton and α-particle spectroscopic factors and branching ratios, needed for the determination of thermonuclear reaction yields. However, also some capture cross sections on stable isotopes have to be known with improved accuracy making facilities for stable isotopes an important complement to the radioactive ion-beams.

X-Ray Bursts For an X-ray burst, the thermonuclear runaway is triggered by the ignition of the triple-alpha reaction and the breakout reactions from the hot CNO cycle. Therefore the on-set of the X-ray burst critically depends on the rates of the alpha capture reactions on ^{15}O and ^{18}Ne. Although recently progress in experimentally determining these rates has been achieved by using either indirect techniques or radioactive ion-beams in inverse kinematics, both rates are not known with the necessary accuracy. The thermonuclear runaway is driven by the αp-process and the rapid proton-process (short rp-process) which convert the initial material rapidly to ^{56}Ni causing the formation of Ni oceans at the neutron star surface. The αp-process is characterized by a sequence of (α,p) and (p,γ) reactions processing the ashes of the hot CNO cycles, ^{14}O and ^{18}Ne, up to the ^{34}Ar and ^{38}Ca range. The rp-process represents a sequence of rapid proton captures up to the proton drip-line and subsequent β-decays of drip-line nuclei processing the material from the argon, calcium range up to ^{56}Ni and beyond. The runaway freezes out in thermal equilibrium at peak temperatures of around 2.0 to 3.0 billion degrees Kelvin. Re-ignition takes place during the subsequent cooling phase of the explosion via the rp-process beyond ^{56}Ni. The nucleosynthesis in the cooling phase of the burst alters considerably the abundance distribution in atmosphere, ocean, and subsequently crust of the neutron star. This may have a significant impact on the thermal structure of the neutron star surface and on the evolution of oscillations in the oceans.

To verify the present models nuclear reaction and structure studies on the neutron deficient side of the line of stability are essential. Measurements of the break-out reactions will set stringent limits on the ignition conditions for the thermonuclear runaway, measurements of alpha and proton capture on neutron deficient radioactive nuclei below ^{56}Ni will set limits on the time-scale for the actual runaway, but will also affect other macroscopic observables. Recent simulations of the X-ray burst characteristics with self-consistent multi-zone models suggested a significant impact of proton capture reaction rates between A=20 and A=64 on expansion velocity, temperature and luminosity of the burst. Clearly, more experimental data are necessary to remove the present uncertainties.

Nuclear structure and nuclear reaction measurements near the doubly-closed-shell nucleus ^{56}Ni determine the conditions for the re-ignition of the burst in its cooling phase. Structure and reaction measurements beyond ^{56}Ni, in particular the experimental study of 2-proton capture reactions bridging the drip-line for even-even $N = Z$ nuclei like ^{68}Se and ^{72}Kr etc., are necessary to determine the final fate of the neutron star crust. These reaction measurements have to be complemented with decay studies. Of particular importance are beta-decay studies of isomeric and/or thermally populated excited states, which are not accessible by experiment with present equipment. In general there is a substantial need for nuclear structure information at the proton drip-line, especially in the Ge - Kr mass region and most likely up to the Sn-Te-I mass range where the endpoint of the rp-process is expected. The information needed to calculate the flow of nuclear reactions in X-ray bursts includes masses, lifetimes, level structures, and proton separation energies.

7.5.3 R-process

About half of the elements beyond Fe are produced via neutron-captures in very neutron-rich environments. The existence of abundance peaks, connected with the major neutron shell-closures, witnesses that neutron-captures have occured far from the valley of stability. Observations of r-process abundances in ultra-poor metal stars by the Hubble Space Telescope reveal what happened in the early age of the Galaxy, when primordial r-nuclides were formed. It is remarkable to see that the abundances of heavy-mass nuclei (beyond A=130) are solar-like and very similar in those stars, although they originate from very different regions of the galactical halo. Therefore, the robust r-abundance pattern above A=130 may be a signature of a unique early “main” r-process of primary nature. Below A=130, one observes “underabundances” in these stars compared to solar ones, with a strong odd-even-Z staggering, which is not present in solar r-material. The missing part to the solar pattern reflects the need for a “weak” r-process of secondary nature, supported also by geochemical evidence from meteorites. These observations, added with the measured isotopic abundances of Eu and Ba, are a breakthrough in our view of the r process and of the chemical evolution of the elements.

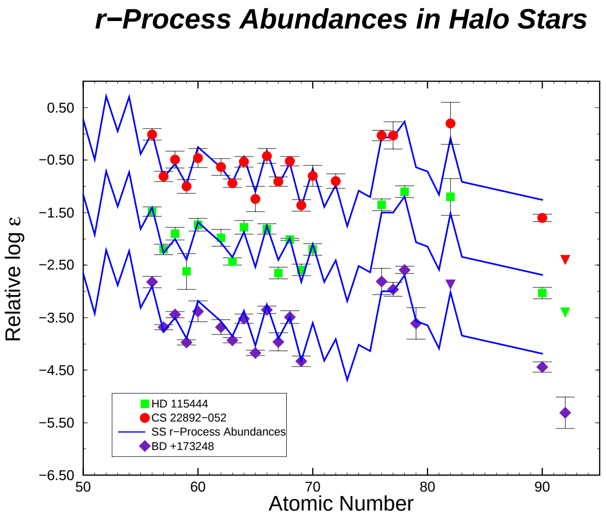

Figure 7.5: Elemental abundances in metal-poor halo stars compared to solar r-material. (Courtesy of J. Cowan)

These findings are supported and supplemented by the abundance patterns of certain refractory inclusions of meteorites which reflect the stellar events in which they were formed. Large isotopic anomalies, with respect to solar, are found in some grains which point to a very neutron-rich production environment. The use of new ionic nanoprobes, which could reveal the composition of sub-micrometer size pre-solar grains, is expected to improve our understanding of the r-process.

Even if the high entropy bubble and neutron-star mergers are likely sites, the exact environment(s), where the r-process(es) occurs, still remains a great mystery at present time. We know, however, that r-process nucleosynthesis is a dynamical process in which the r-process path in the nuclear chart depends on the changing conditions of the stellar environment. In hot and very neutron-dense environments, neutron-captures occur on very short timescales and quickly equilibrate with photo-disintegrations for nuclei with low neutron separation energies. In such cases, the important parameters for modelling the r-process nucleosynthesis are the masses, which fix the location of the waiting points in each isotopic chain, the β-decay half-lives and the P_n values, which determine the amount of r-progenitors accumulated and to which extent their decay occurs via delayed-neutron(s) emission(s). When the r-process matter reaches lower neutron densities, at which β-decay times are shorter than neutron-capture times, branchings in each isotopic chain occur. It is of key importance to determine the three properties (β-decay half-lives, masses and neutron-capture cross-sections), especially at and around the major neutron closed-shells N=50, 82, and 126, associated with the r-abundance peaks. These magic nuclei (called waiting points) have also longer life-times than their non-magic neighbors and regulate the mass-flow and duration of the r-process.

As recent major experimental breakthroughs, the β-decays of about 30 neutron-rich nuclei on the r-process path(s) have been measured at the ISOLDE facility, including those of the $N = 82$ waiting points ^{130}Cd and ^{129}Ag. These new results, added to the previous studies at the N=50 closed shell, are important data needed to put constraints on the astrophysical conditions for the build-up and break-out of the A=80 and A=130 r-abundance peaks.

Atomic masses for nuclei far from stability might hold the key for the understanding of nuclear structure in the yet unexplored parts of the nuclear chart. Their knowledge is particularly essential for r-process simulations. In recent years the GSI at Darmstadt has developed a succesful programme measuring masses of short-lived fission fragments of a high-energy Pb beam using time-of-flight and Schottky methods; as an illustrative example Figure 7.6 shows more than 70 new masses in the $N = 50$ and 82 region obtained at the GSI with the isochronous time-of-flight method. The proposed GSI upgrade with a much higher primary beam intensity and an order of magnitude larger acceptance of the proposed cooler ring promises to measure several hundreds new masses of neutron-rich nuclei, including those of crucial r-process waiting points. Such data are essential to better constrain the location of the r-process for given stellar conditions and will also provide much needed information about potential shell-structure effects. Here, a strongly debated current issue is whether the shell gap in very neutron-rich nuclei (particularly for $N = 82$) is noticeably less pronounced than in stable nuclei. Such an effect would have

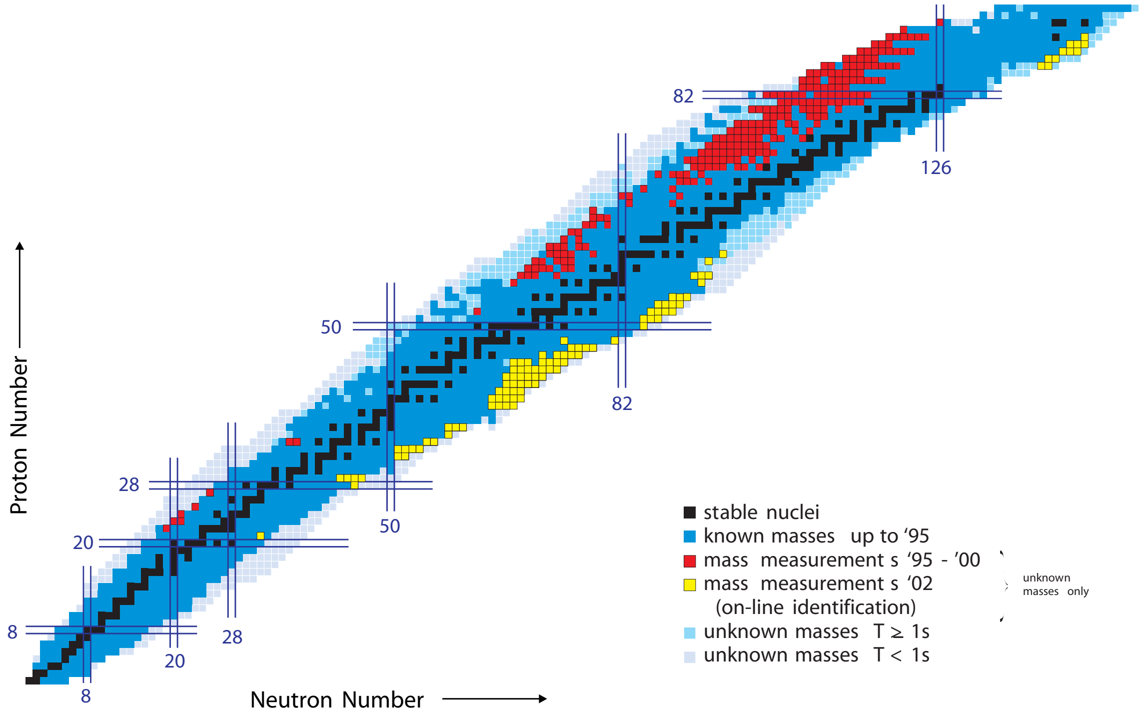

Figure 7.6: The current knowledge of nuclear masses. Preliminary results obtained on-line from the fragmentation or from the fission of a ^{238}U beam are shown in yellow color. (Courtesy of Y. Litivinov)

significant impact on the r-process abundance pattern at the low-A wing of the peaks. Its firm verification, however, needs further experimental study of the r-process progenitor nuclei in the vicinity of the shell closure. In particular, major developments have to be started to produce and study the refractory elements (Mo to Pd) around N=82.

There are currently no data available for r-process nuclei in the region of the N=126 shell closure, which is associated with the third r-process peak at around $A \sim 195$. This is likely to change, when this region can be reached by the high-energy fragmentation of Pb or U beams at GSI. These key experiments will then open a new era in nuclear structure and r-process research, in particular delivering the first measurements of halflives for $N = 126$ waiting points. Beyond $N = 126$, the r-process path reaches regions where nuclei start to fission, demanding an improved knowledge of fission barriers in extremely neutron-rich nuclei to determine where fission terminates the neutron capture flow and prevents the synthesis of superheavy elements with Z>92. If the duration time of the r-process is sufficiently long (as it could be found in neutron star mergers), the fission products can capture again neutrons, ultimately initiating "fission cycling" which can exhaust the r-process matter below $A = 130$ and produce heavy nuclei in the fission region. Fission can in particular influence the r-process abundances of Th and U. This would change the Th/U r-process production ratio with strong consequences for the age determination of our galaxy, which has recently been derived from the observation of these r-nuclides in old halo stars.

The direct measurement of neutron-capture cross sections on unstable nuclei is technically not feasible. This goal can, however, be achieved indirectly by high resolution (d,p)-reaction, which are considered the key tool to study neutron capture cross sections of rare isotopes at radioactive nuclear beam facilities. For r-process nuclides, particular technical advancements need to be made to produce the required beams of a few MeV/nucleon. Studies of beta delayed-neutron decays can help to determine the existence of isolated resonances above the neutron-emission threshold in the daughter nucleus. Such experimental studies will be performed for selected nuclei, in particular at the neutron shell closures, to guide and to constrain global theoretical models. Of particular importance are detailed studies of the soft pygmy resonance which are energetically expected around the neutron threshold and can strongly influence neutron capture cross sections.

7.6 Non-thermal nucleosynthesis

Spallation reactions induced by highly energetic particles, in particular by Galactic Cosmic Rays (GCR), are a well-established production mechanism for several light elements (Li, Be, and B) and for some isotopic anomalies in meteorites. The understanding of the isotopic composition of the GCR at energies around one GeV per nucleon for elements up to Fe, has progressed significantly by observations made with spacecrafts like ACE and ULYSSES and balloon flights. Data for heavier elements are expected for the near future. This data record will serve to elucidate the origin and the source composition of the GCR, as well as their propagation and the associated production of secondary GCR nuclei by fragmentation reactions with H and He nuclei in the interstellar medium (ISM). A reliable modelling of the involved nuclear network is crucial. Of particular importance are the various spallation cross sections in the several hundred MeV to several GeV per nucleon range. Proton induced fragmentation cross sections for most of the light elements were determined at BEVALAC, SATURNE and recently at the GSI fragment separator and an extensive set of accurate data is available to interpret the GCR composition up to Fe/Ni. This effort must be continued to heavier elements and accompanied by theoretical studies to obtain a complete set of cross section data to interpret the observations.

Recent observations of the abundances of the light elements Li, Be, and B in metal-poor stars force us to modify our understanding of the Galactic chemical evolution of these elements. In the standard spallation model it is assumed that these elements are solely made by fragmentation reaction on CNO nuclei in the ISM, induced by fast protons and α-particles in the GCR. However, the new data suggest that significant amounts of Li, Be and B may be produced in OB associations, i.e. groups of stars that are dominated by main-sequence stars of O and B spectral types, via the spallation of accelerated C and O nuclei at energies below several hundred MeV per nucleon. This last process can be dominant in the early Galaxy. Detailed studies of the origin of the particles and their acceleration mechanism in OB associations and in the ISM are clearly needed.

Decisive progress in the solution of these questions is expected from γ-ray astronomy. Many of the nuclear reactions induced by cosmic-ray nuclei are accompanied by prompt de-excitation of excited nuclear levels populated by inelastic scattering, transfer or spallation reactions, or they are followed by delayed γ-ray emission from radioactive species or π^0-particles which are produced in these collisions. The associated nuclear γ rays will be observed by future space missions like INTEGRAL, AGILE and GLAST. For example, these missions will detect strong γ-lines produced in inelastic scattering of cosmic-ray protons and α-particles on nuclei like ^{12}C, ^{16}O and ^{56}Fe, which are abundant in the ISM, and from α-α reactions. As this γ-ray production is most effective for cosmic rays below a few hundred MeV per nucleon, the observed lines and their intensities can be converted into the determination of the cosmic-ray spectrum in this energy range. Similar γ-ray production occurs in strong solar flares. This field will benefit tremendously from the dedicated observations expected from the RHESSI spacecraft.

To make optimal use of the detailed high-resolution spectroscopic informations from INTEGRAL and RHESSI, progress in our knowledge of the various γ-ray emission processes and the completion of the required cross section data base are needed. In particular, differential particle and γ-ray cross sections and particle-γ correlations from threshold to typically one hundred MeV per nucleon must be known to interpret the observed line shapes. To complete the data base, cross sections above the γ-production threshold for proton- and α-induced reactions on the abundant nuclear species in the ISM between ^{12}C and ^{56}Fe are required. This is a task which is well suited for tandem accelerators at university or smaller research laboratories. The experimental efforts have to be accompanied by systematic optical model calculations.

7.7 Nuclear modelling

The specific astrophysical conditions make a direct experimental determination of required nuclear input often impossible. Thus, despite important effort in the last decades to measure astrophysically relevant data, theoretical models are often needed to translate these data from laboratory to stellar conditions. For example, most charged-particle induced reactions at stellar energies, i.e. at energies far below the Coulomb barrier, have cross-sections that are far too low to be measured at the present time (Section 7.3). Stellar reactions often concern unstable or even exotic (neutron-rich, neutron-deficient, superheavy) species for which no experimental data exist. Certain astrophysical applications like the r- or p-processes (see Section 7.5) involve thousands of unstable nuclei for which many different properties have to be determined (including ground and excited state properties, strong, weak and electromagnetic interaction properties). In high-temperature environments, thermal population of excited states by electron or photon interactions, as well as ionization effects significantly modifies the nuclear properties in a way which is impossible to measure in the laboratory. For all these extreme conditions found in astrophysical environments, theorists are requested to supply the required nuclear input if it is experimentally not available.

The description of the many nuclear processes in stars requires a careful and accurate account of all physically relevant input data so that nuclear models have to be "physically accurate" and "globally applicable" at the same time. A global description of all required nuclear input within one unique model ensures a coherent prediction of all unknown data. The need of extrapolating data from experimentally known regions favors microscopic models with a sound first-principle foundation.

Many global microscopic approaches have been developed in the last decades and are now more or less well understood. However, they were almost never used for practical applications, because of their lack of accuracy in reproducing experimental data on a global scale. The low global accuracy mainly originated from computational complications making the determination of free parameters in the models by fits to experminental data time-consuming. This shortcoming has been overcome in recent years and todays microscopic models can be tuned to the same level of global accuracy as the phenomenological multi-parameter models, which have conventionally been used to describe experimentally unknown input in astrophysical scenarios. The following subsections describe some of the advances and future needs in nuclear modelling.

7.7.1 Reaction models

As the degrees of freedom increase drastically with the number of nucleons, models of different sophistication have to be chosen for the various regions in the nuclear chart. Exact calculations using realistic nucleon-nucleon interactions, e.g. by Green's Function Monte Carlo techniques, are restricted to light nuclei. As an alternative, methods based on effective field theory have recently been developed for few-nucleons systems. Both approaches have demonstrated their ability to reliably describe reactions with light nuclei. Other useful tools for the extrapolation of data for reactions of light and certain medium-heavy nuclei are the microscopic cluster model and the continuum shell model. These approaches have the major advantage of providing a consistent description of bound, resonant, and scattering states of a nuclear system and have successfully been applied to determine the low-energy cross sections for many astrophysically important reactions. Despite these successes, more effort in that direction is obviously needed.

For reactions involving heavy nuclei, most of the cross section calculations needed for nucleosynthesis applications are based on the statistical Hauser-Feshbach model. This model makes the fundamental assumption that the process proceeds via the intermediate formation of a compound nucleus in thermodynamic equilibrium. This assumption is justified if the level density in the compound nucleus at the projectile incident energy is large enough to ensure an average statistical superposition of states. However, when the number of available states in the compound system is relatively small, as this is the case for many proton capture reactions in the rp-process, the capture process is mainly dominated by direct electromagnetic transitions to a bound final state. In general, direct reactions play an important role for light, closed-shell or exotic neutron-rich systems for which no resonant states are available.

Both the direct and statistical models have proven their ability to predict cross sections accurately. However, these models suffer from uncertainties stemming essentially from the predicted nuclear ingredients describing the nuclear structure properties of the ground and excited states, and the strong, weak and electromagnetic interaction properties. The description of these fundamental nuclear properties will benefit significantly from recent progress and future advances in microscopic and semi-microscopic models which we will describe in the next subsections.

7.7.2 Ground state properties

Global mass models have recently been derived within the non-relativistic Hartree-Fock and relativistic Hartree methods. Making use of a Skyrme force which has been adjusted to essentially all known masses, it has been demonstrated that the microscopic Hartree-Fock approach can successfully compete in overall reproduction of the measured data with the most accurate empirical droplet-like formulas available nowadays. This quality is achieved not only when the pairing force is described in the BCS approximation, but also when the Bogoliubov method is adopted (HFB model), which treats the nuclear single-particle and pairing properties self-consistently. Although complete mass tables have now also been derived within the HFB approach, further developments which affect the mass extrapolations towards the neutron drip-line are still needed. Moreover, effective interactions for the present state-of-the art mean field models have to be developed which consistently describe the many observables needed (such as giant dipole or Gamow-Teller excitations, infinite nuclear matter properties). These various nuclear aspects are extremely complicated to reconcile within one unique framework and the quest towards universality will most certainly be a focus of nuclear physics research for the coming decade. The study of correlation effects on nuclear masses will benefit from advanced models beyond the mean-field approach, like the shell model or the cluster expansion approaches.

7.7.3 Nuclear level densities

Until recently, only classical approaches were used to estimate nuclear level densities for practical applications. Several approximations used to obtain the nuclear level density expressions in an analytical form can be avoided by quantitatively taking into account the discrete structure of the single-particle spectra associated with realistic average potentials. In a recent global calculation, based on the HF-BCS model, it has been shown that all the experimentally available level density data can be described to an accuracy comparable with the widely used phenomenological formulas. Important effort still has to be made to improve the microscopic description of collective (rotational and vibrational) effects, as well as their dependence on the excitation energy. It looks promising that such calculations can soon be performed within the Shell Model Monte Carlo (SMMC) approach which allows the description of nuclear properties at finite temperature and has recently been successfully adopted to microscopically derive level densities for medium-mass nuclei. The SMMC model considers correlations among valence nucleons by a realistic interaction and, hence, treats pairing correlations in the ground and excited states consistently. Such a coherent description in level density models based on mean-field approaches is still needed. Future global combinatorial and shell model calculations of level densities will significantly improve the reliability of the predictions for exotic nuclei.

7.7.4 Optical potentials

Conventional global optical potentials are parametrized in nuclear astrophysical applications by a Woods-Saxon form. Recently a nucleon-nucleus optical potential has been derived from the Reid hard core nucleon–nucleon interaction within the framework of the Brückner–Hartree–Fock (BHF) approximation. This potential has been empirically renormalized to reproduce scattering and reaction observables for a large set of spherical and quasispherical nuclei in a wide energy range from the keV region up to 200 MeV. However, the asymmetry component in the potential has to be improved to guarantee a reliable and accurate description of extremely neutron-rich nuclei. To achieve this goal BHF calculations of asymmetric nuclear matter would be most useful.

The derivation of reliable α-nucleus optical potentials is much more complicated and the latest developments are rather scarce. The very low energies which are of relevance in astrophysical environments (far below the Coulomb barrier) make the extrapolation of global potentials quite uncertain (see Section 7.5)). For these reasons, new global potential parametrizations of Woods-Saxon or double folding types have been proposed in order to better take into account the strong energy and nuclear structure dependence which affects the absorptive part of the potential at low energies. However, experimental data at low energies (elastic and inelastic scattering, α-capture or (n,α) cross sections) are scarce making the predictive power of the new parametrizations still uncertain.

7.7.5 γ-ray strength functions

The radiative neutron capture rate at energies of relevance in astrophysics is sensitive to the low-energy tail of the giant dipole resonance, in particular if pygmy resonances exist close to the neutron threshold as recently been suggested by some experiments and model calculations. The E1 strength distribution is conventionally described by a generalized Lorentzian model. Due to its importance, however, improved global descriptions are warranted. A first systematic and microscopic attempt to derive global $E1$-strength functions is based on spherical QRPA calculations adopting a Skyrme force. Future calculations should be based on the HFB-QRPA model to guarantee a consistent description of pairing correlations and should consider nuclear deformation and higher-order QRPA effects.

7.7.6 β-decay rates

The reliable calculation of β-decay rates is strongly complicated by the fact that the rates are highly sensitive to the low-energy wing of the spin-isospin response functions introducing a strong nuclear structure dependence. Recently first attempts to derive these rates based on a fully self-consistent HFB plus QRPA description of the ground state and β-decay properties have been made. Although promising, these calculations clearly need improvements. In particular, the global calculations should be based on a mass-independent finite-range effective nucleon-nucleon interaction that ensures a universal and accurate description of the spin-isospin excitations of arbitrary multipolarity in the whole nuclear chart. Furthermore, such fully self-consistent models for spherical and deformed nuclei need to be developed. Currently the reproduction of ground-state properties and the spin-isospin excitation with the same value of the Landau-Migdal interaction (as extracted from experimental data) is an open problem. In addition, the influence of forbidden transitions and higher-order QRPA effects on the β–decay rates need to be studied systematically.

Without doubt, the shell model, which takes all correlations among the valence nucleons into account, represents the method of choice to derive β-decay rates. Due to computational limitations, the model is currently restricted to light or intermediate-mass nuclei, and to nuclei with a single closed shell like the r-process waiting points. Extension of the model to heavier nuclei is certainly needed for future astrophysical applications.

To illustrate the present status of our ability to predict reaction rates, Figure 7.7 shows a comparison of the reaction rates estimated within the statistical Hauser-Feshbach model making use of 14 differents sets of nuclear in-

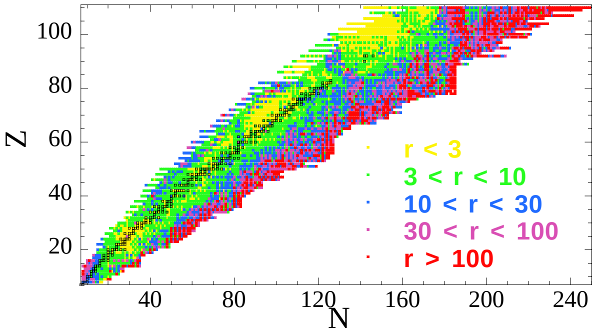

Figure 7.7: The ratio r of the maximum and minimum rates for neutron radiative captures on individual nuclei with charge and neutron numbers Z, N obtained for 14 different sets of nuclear inputs. The different color codings correspond to different r ranges. The adopted temperature is $T = 1.5 \times 10^9$ K. (Courtesy S. Goriely)

gredients, based on macroscopic as well as microscopic inputs as described in the previous subsections. The maximum-to-minimum ratios r reflect the remaining uncertainties affecting the reaction rate estimate for stable as well as unstable neutron-deficient and neutron-rich nuclei. In particular, microscopic models give rise to very different predictions than the widely used macroscopic ones. Much work remains to be done, especially in the neutron-rich region, to improve the reliability and accuracy of the present approaches.

7.8 Recommendations

One of the great attractions of nuclear astrophysics is its diversity, which is not only reflected by its strong interdisciplinary character, but also in the need for a wide span of experimental facilities, ranging from major international laboratories to small university-based research laboratories. We constitute therefore with satisfaction that many European research centers, including the GSI, Ganil, Louvain-La-Neuve, Gran Sasso, INFN, KVI Groningen and CERN, have endorsed a strong programme towards nuclear astrophysics. At the same time, much of the important progress, which we witnessed in recent years, has been achieved by university groups. Both, the activities at the large research centers and at the university laboratories, have to be continued and extended.

At many frontiers in nuclear astrophysics, progress depends decisively on the knowledge of properties of short-lived, exotic nuclei far-off the valley of stability. Determining these properties and experimenting with such short-lived nuclei, as they naturally only occur at the extreme conditions of many astrophysical objects, requires the availability of intense radioactive ion-beams.

Recommendation 1: With highest priority we recommend therefore the immediate construction of the radioactive ion-beam facility at the GSI in Darmstadt. This would make the GSI for many years a world-leader in experimental nuclear astrophysics, ideally supplementing the strong European efforts in astrophysics, cosmology and space research.

Complimentary to fragmentation beams, top-level research in Europe in nuclear astrophysics also requires a second-generation ISOL facility. The construction of EURISOL is therefore highly recommended for the intermediate future.

An immediate upgrade of existing facilities like Spiral at GANIL and Rex-Isolde at CERN to accelerate also heavier nuclei is highly recommended, to bridge the gap until the second-generation radioactive ion-beam facilities are operational.

The Underground Laboratory at the Gran Sasso has proven itself as a worldwide unique facility devoted to measure astrophysically important nuclear reactions to unprecedently low energies, sometimes even reaching the relevant stellar energies.

Recommendation 2: To optimally exploit the unique opportunities, offered by this laboratory, we recommend with very high priority the installation of a compact, high-current 5-MeV accelerator for light ions equipped with a high-efficiency 4π-array of Ge-detectors.

Traditionally a strong component of the nuclear astrophysics research is carried out by smaller university groups and research laboratories. The expertise of these groups is vital for the field. This research is often centred around university accelerators which also hold a potential for interdisciplinary research in other science areas (material research, life science etc.) providing additional training grounds for young researchers. We also point to the broad educational benefits of dedicated experiments at such laboratories allowing young researchers to be responsibly involved from the design phase of the experiment to the data taking and analysis.

Recommendation 3: We recommend, with very high priority, to continue and extend the dedicated nuclear astrophysics programmes built around smaller university and research laboratory accelerators.

Due to the interdisciplinary character of the field, progress in nuclear astrophysics requires an extensive contact and exchange of ideas between theoretical and experimental nuclear physicists and astrophysicists, cosmologists and observers.

Recommendation 4: We recommend a strong initiative to develop the necessary infrastructure to coordinate the specific nuclear astrophysics needs like up-to-date and exhaustive data bases. The European Centre for Theoretical Studies in Nuclear Physics and Related Areas ECT* in Trento offers the ideal environment for such contacts and will continue to play a crucial role here.

Theoretical development should focus on nuclear structure far-off stability, the development of nuclear reaction models which allow more accurate extrapolations of data to astrophysically relevant energies, the nuclear equation of state, neutrino opacities of hot, dense matter, and neutrino emissivities of dense matter in neutron star cores. Theoretical nuclear astrophysics require access to powerful computers and, more importantly, qualified young researchers. This is in particular true for topics related to nuclear structure physics and becomes progessively important once the desired data from the new radioactive ion-beam facilties become available and require theoretical explanation and modelling.

Recommendation 5: We recommend with very high priority the initiation of dedicated programmes to train young researchers in theoretical nuclear astrophysics and the creation of related positions at universities and research laboratories.

8. Fundamental Interactions

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8.1 Forces and symmetries

Symmetries play an important and crucial role in physics. Global symmetries give rise to conservation laws and local symmetries yield forces. Four fundamental interactions are known to date:

- Gravitation,
- Weak Interactions,
- Electromagnetism, and
- Strong Interactions.

The Standard Model (SM) provides a theoretical framework in which Electromagnetic, Weak and many aspects of Strong Interactions can be described to astounding precision in a single coherent picture. A major goal in modern physics is to find a unified quantum field theory which provides a description of all the four fundamental forces. Nowadays the description of Strong Interactions presents challenges particularly at low energies which are covered in this report in a dedicated chapter on QCD. A satisfactory quantum description of gravity remains yet to be found and is a lively field of actual activity.

The Standard Model has three generations of fundamental fermions which fall into two groups, leptons and quarks. The latter are the building blocks of hadrons and in particular of baryons, e.g. protons and neutrons, which consist of three quarks. Forces are mediated by bosons: the photon, the $W^{\pm}$- and Z^0-bosons, and eight gluons. In the SM the number of baryons is conserved and several different lepton number conservation laws hold. Leptons are special through their insensitivity to strong interactions. For quarks the mass eigenstates and the eigenstates for weak interactions are not identical. Their mixing with which they participate in interactions is governed by the Cabbibo-Kobayashi-Maskawa (CKM) matrix. Recent observations of neutrino oscillation experiments demonstrate that neutrino flavours mix, too. Investigations of the nature of these processes and the behaviour of neutrinos rank among the top urgent questions in physics.

Here we are concerned with important implications of the SM and centrally with searches for new, yet unobserved interactions. Such are suggested by a variety of speculative models in which extensions to the present standard theory are introduced in order to explain some of the not well understood and not well founded features in the SM. Among the intriguing questions are the hierarchy of the fundamental fermion masses and the number of fundamental particle generations. Further, the electro-weak SM has a rather large number of some 27 free parameters which all need to be extracted from experiments. It remains very unsatisfactory that the physical origin of the observed breaking of discrete symmetries in weak interactions, e.g. of parity (P), of time reversal (T) and of combined charge conjugation and parity (CP), remains unrevealed, although the experimental facts can be well described within the SM. The role of CP violation is of particular importance through its possible relation to the observed matter-antimatter asymmetry in the universe. This connection is one of the strong motivations to search for additional sources of CP violation [1].

The speculative models beyond the present standard theory include such which involve left-right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which in their low energy limit may include supersymmetry.

In the electro-weak part of the SM very high precision can be achieved for calculations, in particular within Quantum Electrodynamics (QED), which is the best tested field theory we know and a key element of the SM. QED allows for extracting accurate values of important fundamental constants from high precision experiments on free particles and light bound systems, where perturbative approaches work very well for their theoretical description. The obtained numbers are needed to describe the known interactions precisely. Furthermore, accurate calculations provide a basis to searches for deviations from SM predictions. Such differences would reveal clear and undisputed signs of New Physics and hints for the validity of speculative extensions to the SM. For bound systems containing nuclei with high electric charges QED resembles a field theory with strong coupling and new theoretical methods are needed. Experiments at Nuclear Physics facilities at low and intermediate energies offer in this respect a variety of possibilities which are complementary to approaches in high energy physics and in some cases exceed those significantly in their potential to steer physical model building.

Within the next decade the theoretical and experimental activities in the field of fundamental interactions will therefore consist of two important directions: (i) the search for physics beyond the SM in order to base the description of all physical processes on a conceptually more satisfying foundation, and (ii) the application of SM knowledge to extract fundamental quantities and to achieve a description of more complex physical systems, in particular of atomic nuclei. Both goals can be achieved at upgraded present and novel to be built facilities.

8.2 Fundamental Fermions

8.2.1 Neutrino Oscillations

Within the last few years our knowledge of basic neutrino properties has dramatically changed. What has been supposed from solar and atmospheric neutrino experiments for quite a while we know now with evidence: neutrinos can transform from one flavor species into another one. The most likely explanation are "neutrino oscillations" (see box on page 143).

Specific oscillation signals besides the disappearance of the initial neutrino flavor are the appearance of a new neutrino flavor or a distinct spectral distortion of the energy spectrum. Neutrino oscillation experiments are sensitive to the mixing parameters $U_{\alpha i}$ and to the difference of the squared masses of the two neutrino mass eigenstates $\Delta m^2_{\mathrm{ij}} = |m^2(\nu_{\mathrm{i}}) - m^2(\nu_{\mathrm{j}})|$. The current results allow to describe each neutrino oscillation case in a reduced 2-flavour space with one difference of squared masses Δm^2_{ij} and one mixing parameter only.

The Super-Kamiokande experiment in Japan has measured the angular deficit of up-going atmospheric neutrinos clearly pointing towards the oscillation of muon neutrinos into non-electron neutrinos, most probably into tau neutrinos at maximum mixing and a difference of squared neutrino masses of about $\Delta m^2 \approx 2.5 \cdot 10^{-3}$ eV^2.

The long-standing solar neutrino deficit clearly seen by the Chlorine and by the water-Cherenkov detectors [2] as well as by the Gallium radio-chemical experiments appears to be caused by solar electron neutrinos oscillating into muon and tau neutrinos. The SNO

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[1] A. Sakharov has suggested that the observed dominance of matter could be explained via CP-violation in the early universe in a state of thermal non-equilibrium and with baryon number violating processes. CP violation as described in the SM is insufficient to satisfy the needs of this elegant model.

[2] R. Davis and M. Koshiba received the Nobel Price 2002 for leading early experimental activities which resulted in the discovery of the solar neutrino deficit and the observation of supernova neutrinos.

Neutrino Oscillations

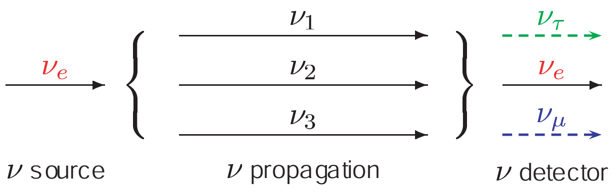
Neutrino mixing

Similar to the quark sector (see box on page 148, the neutrino flavor eigenstates ν_e, ν_μ and ν_τ, which are defined by being the partners of e, μ and τ in charged current weak interactions, are not necessarily identically to the mass eigenstates ν_1, ν_2, ν_3, but are superpositions of the latter. The neutrino mass basis ν_i and the neutrino flavor basis ν_α are then connected by a unitary mixing matrix U.

$$\begin{pmatrix} \nu_\mathrm{e} \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino oscillation

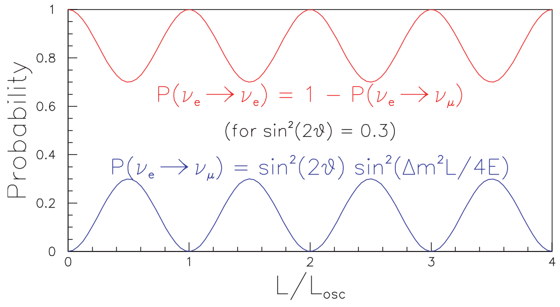
The existence of neutrino oscillation requires neutrino mixing and differences in neutrino masses (and therefore non-zero neutrino masses). When a neutrino is created with a certain flavor by a weak interaction process (*e.g.* a ν_e in the sun) and it moves towards a detector, its propagation has to be described not in terms of flavor eigenstates ν_α but in terms of mass eigenstates ν_i. Therefore, the weak eigenstate has to be transformed into a sum of mass eigenstates ν_i, which propagate independently.



If the contributing mass eigenstates $m(\nu_\mathrm{i})$ differ in mass, phase differences are accumulated during the flight. Since at the detector the neutrinos are detected by a weak interaction, the transformation has to be reversed again. The various contributions need to be added coherently and not always the same flavor is obtained back. Hence, the ν_e of our example could be converted into a ν_μ or a ν_τ.

As the disappearance of the initial neutrino flavor and the corresponding appearance of another flavor is periodic in the propagation length. This process is called "neutrino oscillation". In a simple case of only two neutrinos the matrix U can be described by a single mixing angle θ. With the difference of the contributing squared neutrino masses Δm^2_ij the transition probability is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(\frac{\Delta m^2_\mathrm{ij} \cdot L}{4E}\right)$$



In case of neutrino propagation through normal matter, the existence of electrons and the absence of muons in normal matter causes a different "diffraction index" for ν_e with respect to ν_μ or ν_τ leading to an additional phase difference due to matter effects. Under some conditions this so-called MSW effect could change the neutrino flavour almost entirely.

(Sudbury Neutrino Observatory) experiment in Canada measures in neutral current reactions as many neutrinos as expected from the solar model, but detects only one third in charged current reactions as electron neutrinos. Combining the different solar neutrino experiments yields 2 regions of possible solutions, which both require strong neutrino mixing.

The most favored theoretical solution, “LMA” (large mixing angle), predicts the difference of squared neutrino masses in the range of $3 \cdot 10^{-5}$ eV^2 $< \Delta m^2 <$ $2 \cdot 10^{-4}$ eV^2, whereas the less favored solution, “LOW” (lower values of mass differences) would require difference in squared neutrino masses of $\Delta m^2 \approx 10^{-7}$ eV^2. In both cases the oscillation parameters are such that matter effects play a significant role in the propagation of the neutrinos through the sun and possibly also through the earth, which is known as the Mikheyev-Smirnov-Wolfenstein or MSW-effect.

The evidence for a third neutrino oscillation reported by the LSND (Liquid Scintillator Neutrino Detector) experiment in Los Alamos, USA, does not fit into the most simple picture of 3 neutrino flavours only. It could not be reproduced by the KARMEN (Karlsruhe Rutherford Muon Electron Neutrino) experiment at the Rutherford Appleton Laboratory (RAL) in England, but also it could not be fully excluded. The dedicated MiniBoone (Mini Booster Neutrino) experiment at Fermilab, USA, has just started and will be able to check the LSND claim within a few years. Until then, there is little motivation to consider oscillation experiments at a future spallation source. However, they might be of relevance for determining astrophysical interesting cross sections (see Chapter 7).

The existence of neutrino flavor transformation is most probably due to neutrino oscillation and therefore requires non-zero neutrino masses. It is a clear signal for physics beyond the SM. The values of the neutrino mixing matrix $U_{\alpha i}$ and of the neutrino masses are sensitive to different possible models beyond the SM. They also have strong consequences for cosmology and astrophysics (see section 8.2.2). Therefore, the hypothesis of neutrino oscillation requires further confirmation and sharpening of the oscillation parameters.

The SNO experiment and the two Gallium radiochemical experiments GNO (Gallium Neutrino Observatory) and SAGE (Russian-American Gallium Experiment) at the Gran Sasso National Laboratory (GSNL), Italy, and in Russia are continuing to take solar neutrino data and to improve the precision. Two new experiments are pinning down the parameter space for solar neutrino oscillation parameters: The long baseline reactor neutrino experiment KamLAND (Kamikoka Liquid scintillator Anti-Neutrino Detector) in Japan has presented first results in late 2002 showing a significant rate deficit, proving the favored “LMA” parameters to be the correct solution (see figure 8.1) The solar ^{7}Be neutrino experiment BOREXINO at GSNL will start soon. The focus of future activities will be a precise determination of the oscillation parameters.

Future solar neutrino experiments will provide real time detection, high statistics, very low threshold to measure the pp neutrinos, and spectral resolution. The difference between elastic scattering, e.g. XMASS (Xenon massive detector for solar neutrino) in Japan, and charged current experiments, e.g. LENS (Low Energy Neutrino Spectroscopy) at GNSL, will allow to determine both the electron neutrino and total active flavor content. The interpretation of low energy neutrino experiments (e.g. with solar neutrinos) depend in part on a precise knowledge of neutrino-nucleus reaction cross sections. Few experimental data are available so far and reliable theoretical predictions are needed.

In case that Δm^2 lies in the high-Δm^2 range of the “LMA” solution, e.g. “HLMA” region, the KamLAND experiment would see a suppression of the rate, however could not determine the mixing parameters precisely. A new reactor oscillation experiment with a baseline of ≈ 20 km would then be necessary in order to measure with high accuracy Δm^2 and the mixing angle.

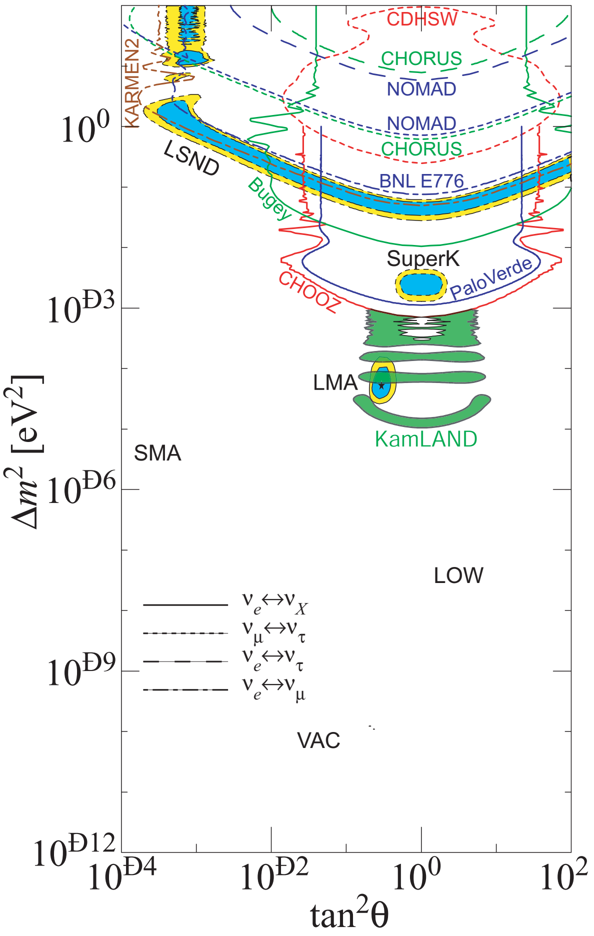


Figure 8.1: Exclusion plot for the three ν oscillation modes $\nu_e \to \nu_\mu$, $\nu_e \to \nu_\tau$, $\nu_\mu \to \nu_\tau$ (marked by different line styles). The cyan (90% C.L.) and yellow areas (95% or 99% C.L.) mark evidences for atmospheric $\nu_\mu \to \nu_\tau$ (SuperK), for solar $\nu_e \to \nu_x$ (LMA), Reactor $\bar{\nu}_e$ disappearence (KamLAND) and for accelerator $\bar{\nu}_\mu \to \bar{\nu}_e$ (LSND) (courtesy of H. Murayama).

The atmospheric neutrino oscillation hypothesis will be checked by long baseline accelerator neutrino experiments under construction. Future neutrino "superbeams" (high flux, low contamination by off-axis beams) or neutrino factories (neutrinos from muons decaying in a storage ring) will allow to approach remaining intriguing questions connected to fundamental interactions: CP violation in the lepton sector, including a CP violating phase and the small mixing matrix element $U_{\mathrm{e}3}$, which are important for leptogenesis.

8.2.2 Neutrino Masses

Neutrino oscillation experiments provide us with the differences of the squared neutrino masses, however, absolute neutrino masses can not be determined. Once one neutrino mass will have been determined by different means, the other neutrino masses could be reconstructed using the Δm^2_{ij} values from neutrino oscillation experiments [3]. The absolute neutrino mass has strong consequences for astrophysics and cosmology as well as for nuclear and particle physics. If the neutrino mass states are hierarchical like the charged fermions, the different neutrino masses would be governed by the square root of Δm^2_{ij}. In contrast the neutrino masses could be quasi-degenerate, but the masses themselves could be much larger, e.g. a few tenth of an eV. Due to the huge relic neutrino density in the universe the latter case would be very important for cosmology concerning topics such as hot dark matter contribution, structure formation and the evolution of the universe. Both scenarios[4] would require different extensions of the SM to describe these neutrino masses. Therefore, determining one neutrino mass absolutely is one of the most important next step in neutrino physics.

Although the observations of the structure in the universe at different scales and of the angular distribution of the fluctuations of the cosmic microwave background radiation allow to set constraints on the hot dark matter content of the early universe and therefore on the neutrino mass, these constraints are model dependent. On the other side, there are strong degeneracies between the different parameters and it is therefore very helpful to supply information from laboratory neutrino mass experiments to determine the other astrophysics parameters more precisely.

Information on neutrino masses by labora-

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[3] To reconstruct the mass scheme unambiguously, it would require to determine the sign of Δm^2_{ij}.

[4] Of course any neutrino mass scenario in between the hierarchical and the quasi-degenerate pattern would be possible.

tory experiments[5] can be inferred using two different approaches: the so-called "direct mass measurements" and the search for neutrinoless double β-decay. Both methods give complementary information on the neutrino masses $m(\nu_\mathrm{i})$. Given the arguments above both methods must reach a clear sub-eV sensitivity in the future.

Direct Mass Measurements

Besides time-of-flight measurements of neutrinos from a strong astrophysical source like a supernova[6] the kinematics of weak decays are investigated: The charged decay products are measured and the neutrino mass is reconstructed using energy and momentum conservation. If the different neutrino mass states $m(\nu_\mathrm{i})$ are not resolved averaged neutrino mass values are obtained, *e.g.*

$$m^2(\nu_\mathrm{e}) = \sum_\mathrm{i} |U^2_\mathrm{ei}| \cdot m^2(\nu_\mathrm{i}) \quad . \tag{8.1}$$

The lowest limits on neutrino masses are coming from β-decay experiments, especially from tritium β-decay: The Mainz Neutrino Mass Experiment is giving an upper limit of $m(\nu_e) < 2.2\ eV$ [7]. A direct sub-eV sensitivity is strongly needed to check the cosmological relevant neutrino mass range and quasi-degenerate mass scenarios.

Experiments measuring the ^{187}Re β-decay with arrays of cryogenic bolometers are in the research and development phase. Their present sensitivity is yet one order of magnitude below the current tritium β-decay experiments, but they are going to improve by enlarging the arrays and the energy resolution. Whether they can reach a sub-eV sensitivity on the neutrino mass is unclear yet. The proposed Karlsruhe Tritium Neutrino (KATRIN) experiment will improve the sensitivity on the neutrino mass by one order in magnitude down to about 0.3 eV. It is based on a huge tritium β-spectrometer which uses the successful technique of Magnetic Adiabatic Collimation combined with an Electrostatic filter (MAC-E-Filter). The experiment combines almost the entire world expertise in this field with the infrastructural benefits of the Forschungszentrum Karlsruhe, Germany.

Neutrinoless Double β-decay

The neutrinoless double β-decay is sensitive to the so-called "effective" neutrino mass

$$m_\mathrm{ee} = |\sum_\mathrm{i} U^2_\mathrm{ei} \cdot m(\nu_\mathrm{i})| \quad , \tag{8.2}$$

which is a coherent sum over all mass eigenstates contributing to the electron neutrino with fraction U_{ei}. The determination of m_{ee} from the measurement of the neutrinoless double β-decay rate is complementary to the direct determination of the mass of the electron neutrino (eq. (8.1)). The values of m_ee and $m(\nu_\mathrm{e})$ could differ for different reasons:

- Double β-decay requires the neutrino to be a Majorana particle.
- The values U^2_{ei} in eq. (8.2) can have complex phases, which could lead to a partial cancellation of the different terms in the sum. Especially, the preference to large mixing as suggested through recent solar neutrino data allows this possibility.
- The uncertainty of the nuclear matrix elements of neutrinoless double β-decay still contributes to the uncertainty of m_{ee} by about a factor of 2.
- Non SM processes, other than the exchange of a Majorana neutrino, could enhance the observed neutrinoless double β-decay rate without changing m_{ee}.

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[5] It should be added that in the SM, extended by non-zero neutrino masses, Dirac neutrinos will have a tiny magnetic moment proportional to their mass. The search for a much larger magnetic moment, and therefore for physics beyond the SM, is currently performed with the MUNU experiment. One motivation was the solar neutrino problem, which now seems to be explained by neutrino oscillation.

[6] Although in case of a galactic supernova the current neutrino detectors would provide much better statistics, the uncertainty of the time distribution of the neutrino emission does not allow to reach a sub-eV sensitivity on the neutrino mass. A new idea is to use neutrinos from gamma ray bursts (GRB) that have time structures on a ms scale. Whether these processes are also connected with the emission of low energy neutrinos, is as unclear as the whole GRB phenomena.

[7] The same limit is given by a second experiment at Troitsk, Russia, but after correcting for a not fully understood effect.

By comparing $m(\nu_e)$ and m_{ee} there is a potential to gain information on CP and Majorana phases and on other physics processes beyond the SM which contribute to the neutrinoless double β decay amplitude.

The lowest limit of $m_{ee} < 0.35$ eV was reported from the Heidelberg-Moscow experiment, which is located in the Grand Sasso underground laboratory in Italy. An array of ^{76}Ge enriched semiconductor detectors is employed. Recently part of the collaboration interpreted the data as a signal for neutrinoless double β-decay. Experiments with much enhanced sensitivity are clearly needed to improve the present result beyond dispute and to allow a meaningful comparison with direct ν mass measurements. NEMO3 (Neutrino Ettore Majorana Observatory) at the Frejus Underground Laboratory in France, CUORICINO (the predecessor of the Cryogenic Underground Observatory for Rare Events (CUORE) and GTF (the Test Facility of the GErmanium NItrogen Underground Setup (GENIUS), both at GSNL, are experiments in the starting phase aiming at a sub-eV sensitivity for m_{ee}. The proposed experiments of the next generation, CUORE and GENIUS in Europe, the American Majorana experiment and the Enriched Xenon Observatory (EXO) and the Japanese/American Mo Observatory Of Neutrinos (MOON) aim to reach a sensitivity below 0.1 eV, by using masses of 1 t of high isotopic abundance and strong background suppression in underground laboratories. Due to the large effort and the limited resources (*e.g.* enriched Germanium) the different approaches should be focused to a few international experiments using complementary techniques and isotopes. On the theoretical side efforts are needed to improve the knowledge of the nuclear matrix elements of neutrinoless double β-decay, which still differ by about a factor 2 for different calculations.

8.2.3 Quarks

Well before the observation of neutrino mixing it had been established that quarks participate in weak interactions with a mixture of their mass eigenstates (section 8.2.1). The mixing is governed by the Cabbibo-Kobayashi-Maskawa (CKM) matrix (see Table 8.1).

The unitarity of this matrix has been put into question by a series of recent experiments. If unambiguously confirmed, such a violation of the SM requirement could be the result, for example, of couplings to exotic fermions, of the existence of an additional Z boson, of supersymmetry or of the existence of right-handed currents in the weak interaction. In models with an extended quark sector an induced neutron electric dipole moment could arise that can be within reach of next generation of experiments.

Due to its large size a determination of $|V_{ud}|$ (see Table 8.1) is most important. It has been derived from a series of experiments on superallowed nuclear β-decays through determination of Q-values and partial lifetimes. With the inclusion of nuclear structure effect and radiative corrections a value of $|V_{ud}| = 0.9740(5)$ emerges in good agreement between different, independent measurements in nine nuclei. The quoted uncertainty, however, is dominated by theory due to the amount, size and complexity of theoretical uncertainties.

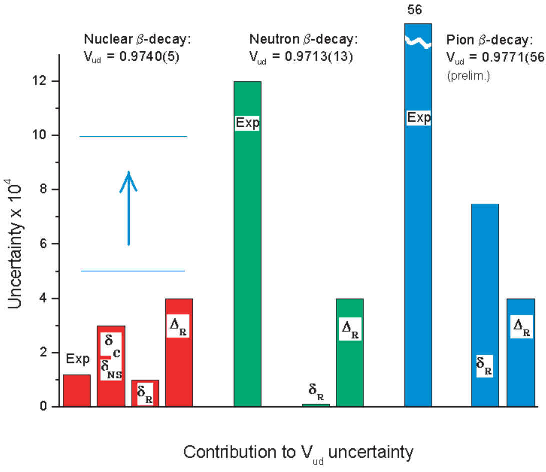


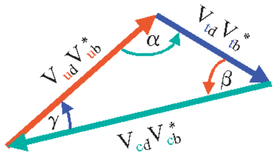
Figure 8.2: Contributions to the uncertainties of the V_{ud} CKM matrix element from experiment (Exp) and theory. δ_R is the transition dependent part and Δ_R is the transition independent part of the radiative correction. For nuclear β -decay there is a radiative correction δ_{NS} from nuclear structure. The arrow indicates the estimated range of the total uncertainty, mainly arising from difficulties in calculations of the structure-dependent isospin breaking correction δ_C.

Quarks and the CKM matrix

Quarks, the building blocks of hadrons, exist in six flavours: up (u), down (d), charm (c), strange (s), top (t) and bottom (b). Mesons like the pion and the eta consist of a quark-antiquark pair, baryons like neutrons and protons are built from three quarks. Similar to the description given for neutrinos (page 143) the quark weak interaction eigenstates do not correspond to their mass eigenstates. As an example, in weak decays the involved quarks carry small contributions from other quarks. This was first recognized by **C**abbibo for the first two quark generations and later expanded by **K**obayashi and **M**askawa to all quarks.
By convention, the u, c and t quarks remain unmixed and all mixing is between the d, s and b quarks. The mixing is expressed in the CKM-matrix V the elements of which can be extracted from weak decays of the relevant quarks. The SM requires the matrix to be unitary. This condition restricts magnitude and phases of the elements; as an example,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \; . \qquad (8.3)$$

The standard parametrization of the unitarity condition uses three angles and a complex phase, which breaks CP invariance. The unitarity triangle is a geometrical representation of eq. (8.3). The angles β and γ are phases of the matrix elements V_{td} and V_{ub}. All processes can be understood by $\gamma = 59° \pm 13°$. The combined results from the BaBar and Belle experiments yield $\beta = 26° \pm 4°$.



So far precision tests of unitarity have only been possible for the first row of the matrix. They are parameterized through

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta, \qquad (8.4)$$

where in the SM Δ vanishes. A possible violation of unitarity of the CKM matrix is a challenge to the three generation Standard Model and could e.g. point to more particle generations.

Although the radiative corrections include effects of order $Z\alpha^2$, part of the nuclear corrections are difficult to calculate. Further, the change in charge-symmetry-violation for quarks inside the nucleus results in an additional change in the predicted decay rate which might lead to a systematic underestimate of $|V_{ud}|$. A limitation has been reached where new concepts are needed to progress. Such are offered by studies of neutron and pion β-decays, where the theoretical situation is more clear due to lower complexity of their structure (figure 8.2).

Recently, $|V_{ud}|$ has been determined using a highly polarized cold neutron beam at the Institut Laue-Langevin (ILL) in France. A value of 0.9713(13) has been extracted from a measurement of the β-p angular correlation (see also section 8.2.5) in the decay $n \rightarrow p\ e^-\ \overline{\nu_e}$ together with the neutron lifetime. This measurement has little sensitivity to corrections for hadronic structure.

The pion β-decay ($\pi^+ \rightarrow \pi^0\ e^+\ \nu_e$) is being measured at the Paul Scherrer Institut (PSI) in Switzerland. The preliminary result is V_{ud}=0.9971(51) with the size of the uncertainty arising from the small branching ratio of this channel and statistics.

The analysis of K_{e3} decays yields $|V_{us}| =$ 0.2196 (23). Hyperon decays can be used to determine this element, however, with lower precision because of theoretical uncertainties in calculating SU(3) symmetry breaking effects in the axial-vector couplings favouring K-decay experiments. The K_{e3}^+ ($K^+ \rightarrow \pi^0 e^+ \nu_e$) and $K_{\mu3}^+$ K_{e3} ($K^+ \rightarrow \pi^0 \mu^+ \nu_e$) branching ratios are based on results of experiments carried out some 20 years ago and on constrained fits. Therefore new dedicated K_{e3} experiments are very desirable.

The element V_{ub} is of no present concern for the CKM unitarity question as its value of $3.6(7) \cdot 10^{-3}$ as determined from LEP and CLEO results is rather small.

Finite values of the unitarity breaking parameter Δ (eq. (8.4)) can be determined, 0.0032(14) using $|V_{ud}|$ from nuclear β-decays and 0.0083(28) from neutron decay. The question whether here a deviation from the SM can be

Table 8.1: CKM quark-mixing matrix with 90%. C.L. The unitarity constraint has pushed $|V_{ud}|$ about one to two standard deviations higher than given by the experiments.

V_{ud} = 0.9741 to 0.9756	V_{us}= 0.219 to 0.226	V_{ub} = 0.0025 to 0.0048
V_{cd} = 0.219 to 0.226	V_{cs} = 0.9732 to 0.9748	V_{cb} = 0.038 to 0.044
V_{td} = 0.004 to 0.014	V_{ts} = 0.037 to 0.044	V_{tb} = 0.9990 to 0.9993

manifested will require advances in the theorectical description of superallowed nuclear, neutron or pion β-decays. Promising results can be expected from neutrons due to their low structure internal sensitivity, if new intense cold and ultracold neutron sources will be available, such as reactor or spallation facilities.

An independent test of CKM unitarity comes from hadronic W decay branching ratios measured at LEP. Since decay into the top quark channel is forbidden by energy conservation one would expect $\sum |V_{ij}|^2$ to be 2 with a three generation unitary CKM matrix. The experimental result is 2.032(32), consistent with eq. (8.3) but with considerably lower accuracy.

8.2.4 Rare Decays

Most unstable elementary particles exhibit typically several decay modes. The dominating modes can be exploited to determine precise values of fundamental constants. As an example, the Fermi coupling constant in weak interactions G_F can be obtained through the lifetime measurement in the muon decay $\mu^+ \rightarrow e^+\nu_e\overline{\nu_\mu}$. This is pursued in three actual experiments at PSI and at RAL. [8]

Rare decay modes may offer access to parameters of other than the dominating interaction. For such experiments state-of-the-art experimental techniques are required. Often the radiation hardness and rate acceptance capabilities of detectors are limiting factors. Therefore such experiments contribute strongly towards advances in radiation detector technology.

In Europe rare meson decays of the π's and the η are studied at PSI and at the The Svedberg Laboratory (TSL), Sweden, in order to extract SM parameters, investigate chiral perturbation theory and to search for symmetry violations such as C- and CP-violation. The pion β-decay, with a branching ratio of 10^{-8}, not only offers a clean possibility to determine CKM matrix element V_{ud} but also provides a test of the CVC (conserved vector current) hypothesis. η decays have provided most sensitive tests of charge conjugation invariance and improvements are expected from the new measurements.

The technical challenges are even higher for the attempts to observe forbidden decays, where branching ratio limits can be even significantly lower. Due to their prominent role, the clean New Physics potential and their requirements on medium energy facilities we will focus here on processes which violate baryon number, global lepton number and lepton flavour.

Baryon Number Violation

In this field low energy experiments allow to probe New Physics at mass scales far beyond the reach of present accelerators or such planned for the future and at which predicted new particles could be produced directly. Generally, in most models which aim for the Grand Unification of all forces in nature baryon number is not conserved. This has lead over the past two decades to extensive searches for proton decays into various channels. Present large neutrino experiments have in part emerged form proton decay searches and the present detectors are well suited to perform these searches along

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[8] Muon decay serves as a reference standard for, e.g., superallowed nuclear β-decays. This is motivated because of its clean description by V-A weak interaction theory and the absence of structure effects in all involved particles.

Baryon and lepton numbers

In the SM baryon number (B) and lepton number conservation reflect accidental symmetries. There exist a total lepton number (L) and a lepton number for the different flavours and different conservation laws which were experimentally established. Some of these schemes are additive, some obey multiplicative, i.e. parity-like, rules.

Based on a suggestion by Lee and Yang in 1955 there is a strong believe in modern physics that a strict conservation of these numbers remains without a foundation unless they can be associated with a local gauge invariance and with new long-distance interactions which are excluded by experiments. Since no symmetry related to lepton numbers could be revealed in the SM, the observed conservation laws have no status in physics. However, the conservation of the quantity (B-L) is required in the SM for anomaly cancellation. Baryon number, lepton number or lepton flavour violation appear natural in the framework of many speculative models beyond the SM and often with probabilities reaching up to the present established limits (see table 8.2).

The observations of the neutrino-oscillation experiments (see section 8.2.1) have demonstrated that lepton flavour is broken and only the total additive lepton number has remained unchallenged. Searches for charged lepton flavour violation are practically not affected in their discovery potential by these neutrino results. For example, in a SM with massive neutrinos the induced effect of neutrino oscillation into the branching probability $P_{\mu\rightarrow e\gamma}$ of the possible decay mode $\mu \rightarrow e\gamma$ is of order

$$P_{\mu\rightarrow e\gamma} = \Delta m^2/400eV \cdot 10^{-39}. \qquad (8.5)$$

This can be completely neglected in view of present experimental possibilities. Therefore here is a clean possibility to search for New Physics at mass scales far beyond the reach of present accelerators or such planned for the future and at which predicted new particles could be produced directly.

with neutrino detection. Up to now numerous decay modes have been investigated and partial lifetime limits could be established up to the 10^{33} year region. One can expect these efforts to be continued with existing setups over the next decade. In general the detectors with the largest mass have highest sensitivity.

An oscillation between the neutron and its antiparticle ($n - \overline{n}$) would violate baryon number by two units. Two in principle different approaches have been employed in the latest experiments. Firstly, such searches were performed in the large neutrino detectors, where an oscillation occurring with neutrons within the nuclei of the detector's material could have been observed as a neutron annihilation signal in which 2 GeV energy are released in form of pions. Secondly, at ILL a beam of free neutrons was utilized. A suppression of an oscillation due to the lifting of the energetic degeneracy between n and $\overline{n}$ was avoided by a magnetically well shielded conversion channel. Both methods have established a limit of 1.2×10^8 s for the oscillation time. Significantly improved limits are expected to emerge from experiments at new intense ultracold neutron sources.

Lepton Number and Lepton Flavour Violation

Neutrinoless double beta decay (see section 8.2.2) probes total lepton number violation. It is not only important for studying the nature of the neutrinos, but also as a tool for searching for other new lepton number violating interactions.

To present date highest accuracy for lepton flavour violation has generally been reached in dedicated search experiments particularly such on kaons (K) and on muons (μ) (see Figure 8.3). The decays of heavier elementary particles, however, which can be created in high energy collisions can be observed with lower accuracy in general and their potential to limit speculative models (or verify their predictions) is mostly restricted to theories in which particle masses enter with high powers.

At present there are two major rare decay muon projects underway: the MEG ($\mu \rightarrow e\ \gamma$)

Table 8.2: Recent upper limits on total lepton number and lepton flavour violating processes (90% C.L.). Expected limits from ongoing experiments and the possibilities at future facilities are given.

decay	limit	experiment	present activities	future possibility
$K_L \to \mu e$	$4.7 \cdot 10^{-12}$	BNL E871		$\approx 10^{-13}$
$K_L \to \pi^0 \mu e$	$3.1 \cdot 10^{-9}$	KTeV		$\approx 10^{-13}$
$K^+ \to \pi^+ \mu e$	$4.8 \cdot 10^{-11}$	BNL E865		$\approx 10^{-13}$
$\mu^+ \to e^+ \nu_\mu \overline{\nu}_e$	$2.5 \cdot 10^{-3}$	KARMEN		
$\mu \to eee$	$1 \cdot 10^{-12}$	SINDRUM I		$\approx 10^{-16}$
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$	MEGA	$5 \cdot 10^{-14}$	10^{-15}
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$6.1 \cdot 10^{-13}$	SINDRUM II	$5 \cdot 10^{-17}(Al)$	10^{-18}
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}$	$1.7 \cdot 10^{-12}$	SINDRUM II		
$B^0 \to \mu e$	$5.9 \cdot 10^{-6}$	CLEO		
$\mu^+ e^- \to \mu^- e^+$	$8.1 \cdot 10^{-11}$	MACS		10^{-13}
$\tau \to e\gamma$	$2.7 \cdot 10^{-6}$	CLEO	$\approx 10^{-7}$	
$\tau \to \mu\gamma$	$3.0 \cdot 10^{-6}$	CLEO	$\approx 10^{-7}$	
${}^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se}\ \ e^- e^-$	$T_{1/2} > 1.2 \cdot 10^{25} y$	HD-MOSCOW	$> 6 \cdot 10^{28} y$	
	$m_{\nu_e}(Maj.) < 0.35 eV$		$0.1 eV$	$< 1 meV$

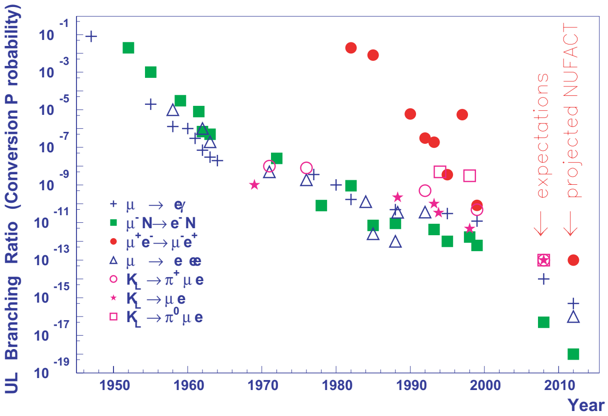


Figure 8.3: Dedicated searches for lepton number and lepton flavour violating processes involving muons (μ) and kaons (K). Recent K experiments and $\mu^+e^- - \mu^-e^+$ conversion show the most significant gain in sensitivity. The steady increase in sensitivity is due to both improvements in experimental techniques and in the available particle fluxes at accelerators. Projections of possibilities of ongoing activities by their experimenters as well as those of a CERN working group for a neutrino factory (NUFACT, 4MW proton driver) are shown.

experiment at PSI and the MECO ($\mu^-\ Al \to e^-\ Al$) experi ment at BNL. They aim for sensitivities at $5 \cdot 10^{-14}$ respectively $5 \cdot 10^{-17}$. At these levels there exist predictions from supersymmetric models. The decay $\mu \to e\ \gamma$ is of particular importance in connection with generic lepton compositness models. The MEG experiment is designed to utilize the presently most intense muon source. It relies on a high overall detection efficiency in a novel detector concept which includes a liquid Xe calorimeter for the γ. MECO relies on its own and yet to be built intense muon source and a novel signature to reduce accidental background caused by ordinary muon decay.

The decay $\mu \to e^+\ e^-\ e^+$ has a similar high potential, however, the realization of an experiment has so far been hindered because the allowed decay $\mu^+ \to e^+\ \nu_e\ \overline{\nu_\mu} e^-\ e^+$ is a potential background source the reduction of which requires thorough energy/momentum measurements of all three electrons in the final state. The conversion of muonium to antimuonium ($\mu^+e^- \to \mu^-e^+$) is of particular interest because it violates lepton flavour by two units (unlike e.g. $\mu \to e\gamma$) . The latest experiment has been driven to the statistics limitation imposed by available muon beam rates. An improved search for this process, which is formally completely analogous to the K^0-$\overline{K^0}$ oscillations in the quark sector, could be carried out at facilities with at least two to three orders of magnitude increased muon fluxes.

8.2.5 New Interactions in Nuclear and Muon β-decays

Already in the 1960's experiments in nuclear β-decay have shown the weak interaction to be predominantly of V-A character. Soon after, this V-A theory was incorporated into the SM. Although today the V-A theory is still in agreement with all experimental data, other interactions could still participate at the 10% level.

In β-decay new interactions can be probed by precision experiments which measure several types of correlations between the spins and momenta of the particles involved in β-decay. Thus, the presence of exotic interactions (e.g. scalar S and tensor T) can be investigated, as well as the masses and couplings of the corresponding bosons that are related to such new interactions. Both neutron and nuclear β- decay are being studied. In the first case the precision is not affected by nuclear structure corrections. However, in nuclear β-decay nature provides a large amount of nuclear states with different properties so that transitions can be selected to yield sensitivity to particular physics beyond the SM and at the same time assure that nuclear structure related corrections are small or well under control.

We will not further consider here a possible pseudoscalar contribution to β-decay, since this vanishes in the non-relativistic approximation for nuclei while, in addition, a very stringent constraint ($\simeq 10^{-4}$ level) was obtained from the pion-decay branching ratio $\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$. The new interactions can have time reversal (T) invariant and time reversal violating components. The latter will be discussed in section 8.3.2.

New Time Reversal Invariant Vector and Axial-Vector Interactions

Precision measurements of observables which are sensitive to right handed (V+A) interactions provide powerful means to probe specific scenarios of new physics beyond the SM in which the maximal violation of parity is restored at some level due to the exchange of non standard new bosons. In nuclear β-decay and in muon decay such observables include asymmetries relative to the spin of the decaying system and longitudinal polarizations of the emitted electrons or positrons.

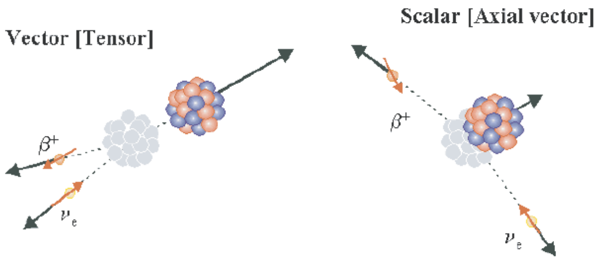


Figure 8.4: Kinematics for the different possible types of β-decay. Fermi β-transitions can proceed through vector (V) and scalar (S) interactions, Gamow-Teller transitions through axial-vector (A) and tensor (T) interactions (for axial-vector and tensor interactions the spin of the positrons has to be reversed). Only vector and axial-vector type interactions have been observed as yet.

Relative measurements comparing the longitudinal polarization of positrons in ^{12}N and ^{107}In decays, emitted along two directions with respect to the nuclear spin, provide so far the most stringent tests of maximal parity violation in nuclear β-decay. The comparison between the electron (A_n) and the neutrino (B_n) asymmetries in neutron decay has also reached a comparable level of precision. In such relative measurements the uncertainties associated either to the degree of polarization of the decaying system or to the analyzing power of the polarimeter are strongly reduced. The measured quantities have reached a level of precision of few parts in 10^{-3}. All measurements so far are consistent with the SM predictions.

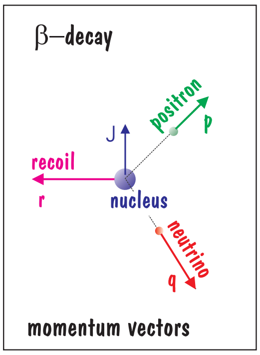
An example of a scenario where parity violation is not maximal is provided by Left-Right symmetric models, involving only vector and axial vector couplings but allowing the presence of right-handed gauge bosons. In the most simple extension, assuming no mixing between bosons, the experiments in nuclear β-decay provide limits on the mass of hypothetical right-handed gauge bosons at the level of about 300 GeV/c^2. Within the same scenario, the limits obtained by precision measurements in muon decay are at the level of 400 GeV/c^2. Despite these efforts these limits turn out not to be competitive with those obtained from direct searches of new heavy charged bosons performed at colliders, which are closer to 700 GeV/c^2. However, within generalized left-right symmetric extensions to the SM, these results cannot be compared on the same

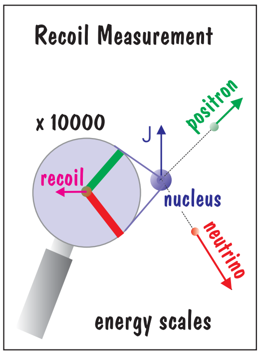
Correlation coefficients in β-decay

In β-decay a parent nucleus with spin $\boldsymbol{J}$ emits a positron (electron) with momentum $\boldsymbol{p}$ and spin $\boldsymbol{\sigma}$ and an electron (anti)neutrino with momentum $\boldsymbol{q}$. The double differential decay probability can be written in its most general form by

$$
\begin{aligned}
\frac{\mathrm{d}^2 W}{\mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \sim\ & 1 \ + a\,\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\,\Gamma\,\frac{m_e}{E} \\
& + \langle \boldsymbol{J} \rangle \cdot \left[A\,\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\,\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E} \right] \\
& + \langle \boldsymbol{\sigma} \rangle \cdot \left[G\,\frac{\boldsymbol{p}}{E} + Q\,\langle \boldsymbol{J} \rangle + R\,\langle \boldsymbol{J} \rangle \times \frac{\boldsymbol{p}}{E} \right]
\end{aligned}
$$

For example, the discovery of parity violation was made from the observation that the spin correlation coefficient A was non-zero. Eventually it lead to a description in terms of exclusively vector (V) and axial-vector (A) interactions, i.e. the V-A theory, as part of the SM. From this theory the value of the correlation coefficients follow depending further only on the structure of the initial and final states. In the SM b vanishes and the T violating contributions to D and R are very small.





$$\langle \vec{J}\cdot\vec{p}\times\vec{q} \rangle \neq 0 \ \ ?$$

$$\mathrm{E}_{\mathrm{recoil}} = \frac{(\vec{p}+\vec{q})^2}{2\mathrm{M}_{\mathrm{recoil}}} < 100\,\mathrm{eV}$$

Selecting the appropriate initial and final states one can select either the V or A interaction in Fermi or Gamow-Teller β-transitions, respectively, allowing one to search for scalar (S) or tensor (T) contributions by observing the characteristic decay.

In practice the neutrino momentum $\boldsymbol{q}$ can not be measured. To measure the full correlation it is necessary to measure the recoil momentum $\boldsymbol{r}$ of the nucleus. The accuracy of these measurements is hampered by the low kinetic energies, E_{recoil}, of the recoil. A breakthrough in precision is emerging exploiting ion and atom traps to suspend the radioactive sample, allowing to measure the direction and energy of the recoil most accurately.

ground due to the different sensitivities to combinations of the coupling parameters. Moreover, parity restoration mechanisms which involve quark-lepton interactions cannot directly be probed in the pure leptonic muon decay. In such context any new effort at low energies to search for the effects of new bosons in the mass range between 500 GeV/c^2 and 1 TeV/c^2, is strongly valuable.

Recently the proof of principle for the measurement of the electron decay asymmetry in nuclear decays using magneto-optical traps has been demonstrated at Los Alamos, USA, with ^{82}Rb atoms. Present efforts to improve the precision on parity sensitive observables include asymmetry measurements with nuclei and neutrons, relative measurements of the positron polarization in the decay of polarized muons, and high resolution measurements of the positron spectrum in muon decay at TRIUMF.

Much of the progress performed in the last decade has been due to the development of new nuclear polarization techniques or to the efficient use of existing ones. Initiatives oriented towards the production of highly polarized, high intensity and high purity sources deserve consideration.

New Time Reversal Invariant Scalar, Tensor and Pseudoscalar Interactions

For S- and T-type interactions, new measurements of the beta-neutrino correlation a (sensitive to S- and T-interactions) as well as of the beta emission asymmetry A (mainly sensitive to a T-interaction) should be carried out. These will at the same time yield information on the Fierz interference term b (sensitive to S- and T-interactions). The beta-neutrino correlation coefficient a is measured with unpolarized nuclei. To measure the beta emission asymmetry parameter A, polarized nuclei are needed. This can be achieved either with the method of low temperature nuclear orientation or by in-beam techniques. For both a and A sub-percent precision was recently achieved.

A significant gain in precision as well as improved reliability for both correlations can be expected from the recent development of atom and ion traps for weak interaction studies. The use of traps will provide very thin sources in vacuum, thus avoiding the need for a material host and allowing to reduce significantly the effects of scattering as well as to detect the recoil ions after beta decay without the disturbing effects of energy loss in the host material. Most trap-based set-ups will initially focus on the beta-neutrino correlation. First β-ion coincidence measurements from decays using isotopes trapped in a magneto-optical trap (MOT) have been carried out at TRIUMF and future results look promising. Systems using Penning traps and Paul traps are currently being set up as well. In order that traps can be more widely used for the measurement of different types of correlations in beta decay, and that also a larger variety of polarized nuclei can be studied in traps, new and more generally applicable methods to polarize nuclei in traps or inject polarized nuclei in traps should be investigated and be developed. Further, the experience and results to be gained in the ongoing and planned measurements with traps will show how these set-ups can be further optimized and/or improved in view of second generation experiments at the planned facilities such as the European EURISOL and Rare Isotope Accelerator (RIA) in the USA.

As for the beta emission asymmetry parameter A, significant progress can be expected also from measurements of this correlation using the low temperature nuclear orientation method. As this method allows to induce large degrees of polarization for a wide variety of nuclei, probe nuclei for these measurements can be selected so as to yield a maximal sensitivity. Finally, the construction of new production facilities such as those planned by the EURISOL and RIA projects will also provide new possibilities for weak interaction studies with exotic nuclei as these will significantly extend both the number of accessible nuclei as well as their yields. Especially important for weak interaction studies are the nuclei near the N = Z line, i.e. with nearly equal numbers of protons and neutrons, for which nuclear structure is favourable.

In neutron decay new instruments (such as e.g. the ASPECT retardation spectrometer or methods that bypass the need of measuring the proton energy) should be further developed to allow for beta-neutrino correlation measurements at the percent or even sub-percent level. Indeed, it was recently shown that a combined analysis of several parameters in neutron decay, i.e. the beta-particle and neutrino emission asymmetries (A resp. B), the beta-neutrino correlation (a) and the lifetime of the neutron, provides stringent limits on S- and T-interactions. It was also stated, however, that the present result depends strongly on the limited precision of the beta-neutrino correlation coefficient (presently 5%) and that a measurement of this parameter at the level of 1% would significantly improve these limits. Finally, all lifetime and correlation measurements in neutron decay would benefit significantly from cold and ultracold neutron sources with higher intensities than those presently available.

In the purely leptonic sector additional information on non standard charged current interactions, that is complementary to that obtained in nuclear β-decay and neutron decay, is obtained in muon decay. It is therefore important that new and more precise measurements of the Michel- and related parameters in muon decay are carried out as well.

8.3 Discrete symmetries

8.3.1 Parity

Parity nonconservation in atoms

During the last quarter of a century atomic parity nonconservation (APNC) has proven to be a crucial tool in testing our understanding of the electroweak interaction. The observation of parity nonconservation in atoms (and then in the deep inelastic electron-deuteron scattering) led to the discovery of the weak electron-nucleon interaction due to the neutral currents. These experiments, performed few years before the discovery of Z- and W-bosons, served as important confirmations of the SM. Since then, APNC has greatly developed and provides now stringent quantitative tests of the SM. Together with the precision electroweak experiments at the LEP storage ring at CERN it could be proven that the SM is valid over more than 10 orders of magnitude in momentum transfer. In addition, the remarkable precision of modern APNC experiments has made them an important tool for studying nuclear structure and P-odd nuclear interactions.

Tests of the Standard Model in Atomic Experiments

APNC effects arise from mixing of electronic states with opposite parity, which results in forbidden electric dipole transitions between states of the same parity. The dominant (and nuclear-spin-independent) part of the PNC Hamiltonian depends on the “weak charge” Q_w, which contains the SM coupling constants. The “weak charge” is extracted from the experimental data combined with accurate calculations of the electronic wave functions. The last experimental result for the weak nuclear charge Q_w of ^{133}Cs, combined with recent theoretical calculations, reads $Q_w = -72.90(28)_{exp}(35)_{th}$, to be compared with the SM prediction $Q_w = -73.09(03)$. Moreover, in these experiments the nuclear anapole moment has been discovered. High precision measurements of these kind together with improved atomic calculations, are expected to have significant implications for the electroweak theory. For instance, many alternatives to the SM imply the presence of a second neutral vector boson Z'^0. In the 100 GeV energy range one is sensitive to the Z'^0 through its mixing to the Z^0, whereas in atomic physics sensitivity is achieved without any mixing, with Q_w proportional to $(\mathrm{M}_{Z^0}/\mathrm{M}_{Z'^0})^2$.

At low momentum transfer, as is the case in APNC experiments, new particles predicted for instance in supersymmetric models at high mass scales or in technicolor models generate additional electron-quark PNC interactions. Q_w can be sensitive to new corrections, weak isospin-conserving and isospin-breaking, usually described by the parameters S and T, respectively. Precision measurements in systems other than ^{133}Cs, should help in providing information on these new interactions. Ytterbium is an extremely promising case for broadening the measurements: it has a pair of nearly degenerate levels of opposite parity, which leads to the enhancement of PNC effects by two orders of magnitude as compared to cesium. It has also a number of stable isotopes, allowing for a systematic comparison of the deduced Q_w. Barium, samarium and dysprosium are also interesting, since they have the last advantage as well. Very important is the possibility to apply the laser techniques known in atomic beam experiments with atomic and ionic traps that represent novel tools to store and manipulate atoms for precision measurements. Experiments are already under way on single Ba^+ ion confined in a radiofrequency trap. To pin down uncertainties on atomic physics calculations and to make proper cross-checks, it is highly desirable to perform measurements on chains of isotopes of alkalis. Therefore, techniques to produce and trap with high intensity radioactive ions is a crucial area of investigation where first successful results have been recently obtained, in particular trapping of radioactive alkalines (i.e., Na, K, Rb, Fr) has been already demonstrated. Important for APNC is the possibility to test high Z atoms, like francium, since the discussed PNC effect increases roughly as Z^3.

Nuclear Anapole Moments and APNC

The high precision of APNC experiments has opened a new window into parity-violating nuclear forces. The nuclear-spin-dependent APNC effect allows one to measure parity violation within the nucleus. These measurements are highly complementary to the nuclear parity-violating experiments which are being performed at many nuclear facilities. The APNC investigation of P-odd nuclear forces is a first-rate, (almost) table-top nuclear physics. As mentioned above, the cesium APNC experiment resulted in the discovery and accurate measurement (on the level of 6 standard deviations) of the nuclear anapole moment (AM), electromagnetic multipole arising due to PNC in the nucleus. This accurate measurement is supplemented by the theoretical calculations of nuclear AMs of a comparable precision. As to the pertinent atomic calculations, their accuracy in cesium is no worse than 2–3%. Taken together, these experimental and theoretical results certainly belong to the most reliable ones in the investigations of P-odd nuclear forces. A few unsettled problems exist here. One is related to the APNC experiment with thallium. Its result is about 1.5 standard deviations below the theoretical prediction. Then, there is only marginal (at best) agreement between the measurement of the cesium AM and results of some other experimental investigations of P-odd nuclear forces performed with more common nuclear techniques. Obviously, it is highly desirable to clear up the problem of thallium AM. On the other hand, of great importance would be experiments with even-odd isotopes. Their anapole moments depend on a combination of P-odd nuclear constants which is almost orthogonal to that entering the cesium AM (and other odd-even nuclei). In this way the relation between the result of a cesium experiment and those of nuclear experiments will be elucidated. Especially noteworthy here are again the experiments with ytterbium, which has a number of stable isotopes, both even-even and even-odd ones. Not only are the AM manifestations in Yb enhanced by more than two orders of magnitude as compared to the corresponding effects in Cs. For one of the fine-structure components of the upper level in the discussed transition, the AM effect is the only parity-violating one (not contaminated by the PNC induced by Q_w). Then, the ratio of AMs of various even-odd Yb isotopes is extracted from the experimental data without any theoretical uncertainties. At last, even-even Yb isotopes (where the AM effect is absent) are useful here for investigating the systematic errors.

Besides experiments on atoms and singly charged ions there are proposals to verify weak interaction effects in highly charged H- like and He-like heavy ions at RHIC and GSI. Such systems promise relatively large effects from weak interactions due to possible high nuclear charges Z. Rather uncomplicated very accurate calculations of atomic wave functions appear possible. A precision of the extracted parameters well beyond what has been achieved with atomic Cs, would be required to extract principal new information beyond the existence of anapole moments and well established facts about weak interaction, e.g. on the momentum transfer dependence of the weak mixing angle $sin^2\Theta_W$. Yet unprecedented accuracy will be needed for measurements of the energies of the involved atomic states and level splittings. Technologically highly challenging measurements of weak interaction induced asymmetries must be performed.

Parity Violation in Electron Scattering

Parity violating observables in electron scattering experiments on nucleons (or nuclei) are associated with interference between electromagnetic (γ) and weak (Z^0) amplitudes. The PV terms depend on a product of vector and axial couplings which manifest themselves in the electron helicity dependent cross sections. Pioneering experiments in the field were performed at the Stanford Linear Accelerator (SLAC), USA, in the seventies, where powerful techniques were developed and where, together with APNC, a significant test of the SM in the neutral current sector could be achieved. Improvements in the experimental methods and the higher sensitivity available nowadays in polarization measurements allow to investigate novel effects as those coming from the strange quark content of the nucleon and the anapole moments associated with weak currents among quarks and new physics.

The right-left asymmetry A in PV scattering experiments, defined as the ratio of difference and sum of cross sections for right- and left-handed electrons, is a function of the nucleon vector form factors associated with γ ($G^{\gamma}_{E,M}$) and Z^0 ($G^{Z}_{E,M}$) interactions and the nucleon axial form factor (G^{e}_{A}), i.e. $A = f(G^{\gamma}_{E,M}, G^{Z}_{E,M}, G^{e}_{A})$. Using isospin symmetry one can show that the weak (magnetic and electric) form factors are linearly related to the electromagnetic form factors (known at an accuracy level of 1-2 %) and to a small contribution from the strange form factor $G^{s}_{E,M}$. Accurate measurements of A in polarized electron scattering on nucleons allow then to define different bands in a $(G^{s}_{E,M}, G^{e}_{A})$ matrix from which absolute values for the single quantities can be deduced.

Strange quark effects in nucleons is a subject of current interest and several theoretical models have been employed in order to compute $G^{s}_{E,M}$. Strange quarks modify the values of the axial weak couplings of the nucleons and the weak magnetic moments. Several theoretical models have been employed in order to compute $G^{s}_{E,M}$, for instance taking into account loop or pole effects, the first involving a creation of a Λ and K in the proton propagator and the second a fluctuation of a Z^0 into a ϕ meson. At present, however, uncertainties are very large and new experimental data are needed to put tighter constraints on the models.

Precision experiments in the field in the last few years have been carried on with the SAMPLE and HAPPEX set-up's, installed at the Bates Linear Accelerator Center and Jefferson Lab., respectively. In SAMPLE one measures backward scattered electrons from a 200 MeV polarized electron beam on hydrogen target with a large solid angle Cerenkov detector. In HAPPEX one measures the scattered electrons at very forward angles with a lead-scintillator calorimeter. In SAMPLE, the overlap $(G^{s}_{E,M}, G^{e}_{A})$ values obtained in the scattering on hydrogen and deuterium differ from recent calculations, indicating possibly large anapole effects in the nucleon. Future experiments are in preparation to measure $G^{s}_{E,M}$ and G^{e}_{A} over different ranges of momentum transfer by the PVA4 experiment at the MAMI accelerator, Germany, and by the G0 experiment at the Jefferson Laboratory, USA. It should be noted that experiments on parity violating $e^- - p$ scattering has a potential to provide important information on New Physics, for example on new neutral gauge bosons and leptoquarks.

8.3.2 Time reversal and CP violation

Within the assumption of CPT conservation (see section 8.3.3) the observation of CP violation (CPV) or Time reversal violation (TRV) would be equivalent. So far CPV has only been observed for the mass degenerate $K^0 - \bar{K}^0$ and recently in $B^0 - \bar{B}^0$ systems. In the neutral kaon system both indirect ($\Delta S = 2$, mixing) and direct ($\Delta S = 1$, decay) CPV has been found. The knowledge of these systems has been crucial for the description of quark mixing as parametrized in the CKM matrix. One of the successes of the SM is that it can account for the observed CPV very well.

Nonetheless, the existence of other sources of CPV is not ruled out. One important argument why such sources should be considered, is the large matter-antimatter asymmetry in the universe.

Within the standard theory CPV in the neutral D-meson system is predicted to be a rather small effect. Therefore its precision measurement, which is indicated at a future intense antiproton machine, offers a large window for new physics effects.

In nuclear and atomic physics CPV/TRV within the SM can only occur as a second order process. This opens a window of opportunity to search for physics beyond the SM in nuclear and atomic physics. The current upper limits on TRV in nuclear physics are indeed many orders of magnitude away from the SM value. A unified description of all forces is likely to lead to models with larger TRV components than predicted by the SM. Current efforts focus on TRV effects in β-decay and, most importantly, on searches for a permanent electric dipole moment (EDM) of fundamental particles. In fact, the EDM measurements are currently the most effective way to restrict a large class of models, although not all. Which observables and which systems have the best discovery potential depends on the specific extension of the SM. The search for TRV, therefore, needs strong guidance from theory. Searches in nuclear physics should also be compared with studies involving second or third generation leptons and quarks. New accelerators to be built for nuclear physics may create the opportunity to contribute in a significant way to this branch of the field of CPV studies. Here we discuss low energy studies as examples.

Electric Dipole Moments

In Table 8.3 the limits on EDM's for various particles are listed. They illustrate the important role that nuclear and atomic physics can play in pushing the limits on New Physics. The reason is that the EDM, $\vec{d}$, is most conveniently measured from its precession in a strong electric field, which favors long-lived neutral particles. The amount of precession can be observed because the magnetic moment, $\vec{\mu}$, and $\vec{d}$ are coupled: they are both aligned with the spin, as only one vector can exist in a quantum system. The precession of $\vec{d}$ can be measured precisely, but requires that the role of magnetic precession is eliminated or controlled. The charged particles can be bound in a neutral system, e.g. an atom or a molecule. By selecting a system that can be polarized easily, i.e. which has nearly degenerate states of opposite parity, the EDM of the particle of interest can induce a dipole moment in the composite system which is much larger.

The limit on the electron EDM is inferred from the upper limit on the EDM of ^{205}Tl which has an unpaired electron. The electronic structure of Tl has an amplifying effect such that $d_{\mathrm{Tl}} = -585 \times d_e$. The effective electric field that can be generated in TlF molecules be used to estimate the limit on the proton EDM, with an amplifying factor of about 10^5. The neutron EDM measurements are made with ultracold neutrons (UCN) stored in a cell permeated by uniform **E**− and **B**−fields. In the past, systematic errors were dominated by fluctuations in the magnetic field. The current RAL/Sussex experiment at ILL, France, uses therefore a magnetometer based on ^{199}Hg stored in the same cell as the neutrons.

The numerically lowest limit on any EDM has been obtained for ^{199}Hg a table top experiment at the University of Washington, USA. The electronic structure of Hg is thereby advantageous. The nuclear structure of ^{199}Hg makes this system a sensitive probe of CP odd forces inside the nucleus. Certain models predicting the baryon asymmetry in the universe also would predict an EDM in ^{199}Hg corresponding to the current limit.

To explore and search for new systems and methods is highly desirable. With the availability of new production facilities for radioactive

Table 8.3: Current limits on permanent electric dipole moments for several particles (converted to common 95% C.L.). The systems are complementary and each one carries information not obtainable from the others. The New Physics limit corresponds to the highest value which is allowed in speculative models. They serve as an indicator for how much present measurement should be improved.

particle	limit on EDM $\lvert d\rvert$ [e cm] (95% C.L.)	system	New Physics limit [e cm]
e	1.9×10^{-27}	^{205}Tl	10^{-27}
μ	1.05×10^{-19}	rest frame E	10^{-22}
τ	3.1×10^{-16}	$(e^+e^- \rightarrow \tau^+\tau^-\gamma)$	10^{-20}
p	6.5×10^{-23}	^{205}Tl-F	5×10^{-26}
n	7.5×10^{-26}	ultracold neutrons	5×10^{-26}
Λ	1.5×10^{-16}	rest frame E	5×10^{-26}
^{199}Hg	2.1×10^{-28}	^{199}Hg	10^{-28}

ion beams, it is possible to consider a much wider range of isotopes and elements than previously possible. New opportunities can be found in heavy unstable elements. For example, in Ra isotopes an enhancement of a nuclear EDM is expected through close lying states of opposite parity in the atomic electron shell and they also possess enhancing nuclear properties such as octupole deformation. Radium could replace Hg in its leading role for atomic EDM searches since Ra could be a factor of 10^5 more sensitive to CP-odd forces.

In searches for electron EDMs polarizable molecules can be used, e.g. as PbO and YbF. Polarizable molecules have recently been cooled and manipulated analogous to trapped atoms. This may open a new opportunity to take better advantage of the enhancement factors in molecules. Note that the above arguments also hold for parity non-conservation (PNC) measurements. A large polarizability can amplify both TRV and PNC.

For the neutron EDM measurement, important improvements can be made on UCN sources. Ideas exist for techniques that could produce a 1000 fold increase in the counting rate due to a higher UCN phase space density. This might be achieved in producing UCN in superfluid liquid ^{4}He. A different approach is the use of solid deuterium for a next generation of UCN sources. The construction of such a facility at PSI is underway. Both techniques expect to improve the sensitivity by about two orders of magnitude to $10^{-28}e$ cm. Further neutron edm activities are pursued at ILL, Mainz and Los Alamos.

The limit on the muon EDM can be significantly improved by 5 orders of magnitude. At this level models with nonlinear inverse mass scaling for EDMs can be stringently tested. A novel technique has been proposed to exploit the strong motional electric field which the particles experience when moving with relativistic velocities in a magnetic storage ring. The magnetic anomaly precession can be compensated through properly tuned radial electric fields. The spin precession due to an EDM can be observed via the time dependent spatial muon decay asymmetry. The magnetic storage ring technique has also been evaluated for nuclei (particularly also β-radioactive ones) in highly charged ions. A significant number of nuclides with a small reduced magnetic anomaly would be suited for this technique. Alternatively one could attempt to eliminate magnetic fields altogether and confine appropriately polarized particles in an all electrostatic trap.

R and D Coefficients in β-decay

Observables for TRV in particle decay or in reactions, can be constructed by combining appropriate vectors and axial vectors. Here two aspects need to be considered carefully. Firstly, final state interactions (FSI) occur that mimic TRV. To put new limits on the actual TRV amplitude, the FSI need to be kept small and calculable or measureable with appropriate accuracy. Secondly, one needs to consider which extension of the SM one can address. It appears that TRV in nuclear strong interactions can be addressed with more sensitivity from one of the limits on the EDM. For this reason we do not consider here nuclear reactions, although measurements on polarized neutron transmission through polarized targets could still be competitive with the EDM of the neutron. This is associated with the large enhancement factors observed in PNC in these reactions.

Important TRV observables are available in β-decays of both leptons and hadrons (e.g. muon, neutron, nuclei and hyperons). Examples of correlations are

$$\frac{\langle\vec{J}\rangle}{J}\cdot\frac{\vec{p}_e}{E_e}\times\frac{\vec{p}_\nu}{E_\nu}\qquad\text{and}\qquad\vec{\sigma}_e\cdot\frac{\langle\vec{J}\rangle}{J}\times\frac{\vec{p}_e}{E_e},$$

where $\vec{J}$ and $\vec{\sigma}_e$ are the spin of the parent nucleus (lepton) and β-particle, respectively. p_i and E_i are the momentum and energy of particle $i = e, \nu$. Instead of measuring the neutrino, it is necessary to measure the recoiling daughter particle (see page 153), which until recently was only possible in special cases and with limited accuracy. Trapping radioactive nuclei has recently solved this problem as discussed below. The coefficients associated with the two correlations are generally referred to as D and R, respectively. The best limit on D comes at present from ^{19}Ne decay: $D = (0.1 \pm 0.6) \times 10^{-3}$. For neutron β-decay, $D = (-0.6 \pm 1.0) \times 10^{-3}$. For Σ^- a value $D = 0.11 \pm 0.10$ exists. The T violating part of the phase between vector and axial vector couplings is proportional to D. It is $0.073^\circ \pm 0.12^\circ$ for neutrons.

The R coefficient is sensitive to TRV through the tensor and scalar couplings. Information on R comes from ^{19}Ne decay with $R_{\mathrm{Ne}} = 0.079 \pm 0.053$ and ^{8}Li decay with $R_{\mathrm{Li}} = (0.9 \pm 2.2) \times 10^{-3}$. Taking advantage of the different nuclear structure of these nuclei, limits on the tensor and scalar part can be made separately. In neutron β-decay, the R coefficient has not been measured, but a new experiment at PSI is under way with an expected accuracy of 5 x 10^{-3}.

The limits provided by EDM measurements strongly restrict the values that can be expected for R and D. However, the latter can be interpreted with much fewer theoretical uncertainties than the EDM, or they are complementary. For example, in models with leptoquark CP-violation, the best constraints for some of the model parameters come from the knowledge of the D coefficient. Therefore, improving the current limits on D and R is desirable. The emiT (Time Reversal in Neutron Beta Decay) collaboration at the National Institute of Standards and Technology, USA, and the TRINE (Time Reversal Invariance Neutron Experiment) collaboration at ILL will measure D in neutron decay with an expected sensitivity of 1 x 10^{-4}.

A new approach is to measure β-decay correlations by suspending the radioactive sample in an atom or ion trap. In such a trap the recoil and electron direction can be accurately measured and the polarization of the sample could be controlled (see box on page 153). A measurement of D has been proposed at TRIUMF, Canada, using a far-off-resonance trap for ^{37}K. This technique has the promise to break through the limitations of the old methods that currently limit D, as well as other correlation coefficients discussed below. It is foreseen that new experiments can reach the limit where the final-state interactions (FSI) becomes relevant. Fortunately the dependence on electron momentum for the FSI is quite different from that of the D coefficient, which will allow to push the limit further while providing a calibration of the experimental method. The FSI increase with the mass of the parent, and therefore are minimal in neutron decay, where the FSI for D and R have been estimated to be $< 2\times10^{-5}m_e/p_e$ and $< 10^{-3}$, respectively. There is considerable potential in the range of light nuclides which can be trapped and produced copiously at radioactive beam facilities. Given sufficient counting statistics improvement of two orders of magnitude in the D coefficient should be feasible in the foreseeable future.

Pursuing TRV observables in other than nucleonic systems remains of interest for various reasons, for example, the pure leptonic character of the muon system and the absence of electromagnetic final-state interactions. Superior counting statistics could possibly be obtained at the production facilities for muon neutrinos. For hyperons one may consider TRV in β-decay and also consider CPV in comparing the hadronic decays of the hyperon and antihyperon. A proton–antiproton collider such as currently proposed for GSI, Germany, could produce sufficient hyperons to make advances in this field.

8.3.3 CPT invariance

The standard model implies exact CPT and Lorentz invariance. As any deviation from it would indicate new physics, CPT conservation has been tested to a high degree of accuracy. Mostly limits of differences in the properties (like masses, charges, magnetic moments, lifetimes) of particles and their anti-particles were compared and normalized to the averaged values. The K^0-$\overline{K^0}$ mass difference had yielded the best test at 10^{-18}.

Especially atomic physics experiments as well as the muon storage ring experiments provide stringent limits on a possible CPT violation when interpreted in terms of a theoretical approach, which allows to assess experimental results from different fields of physics. Here additional small terms are introduced into the Lagrangian or Hamiltonian of Dirac particles and perturbative solutions are searched for. All possible additions violate Lorentz invariance and some of them break CPT. They are associated with the existence of a preferred frame of reference and therefore diurnal variations in physical observables relating to particle spins can be searched for. Here limits have been established at 10^{-30}GeV for neutrons, 10^{-27}GeV for electrons and protons and 10^{-24}GeV for muons. It remains as a controversial theoretical question, whether the energies associated with CPT breaking terms should be normalized to the mass of the particles in order to arrive at a dimensionless figure of merit for CPT violation, which in such case would be most favourable for electrons and neutrons at about 10^{-30}.

The question to which level CPT as well as Lorentz invariance hold in atomic systems is presently being tackled with experiments at CERN/AD. The ATRAP and the ATHENA collaborations propose a measurement of frequency differences of the antihydrogen compared to the hydrogen atom. The experiments aim at an ultimate relative uncertainty of 10^{-18} for a determination of the 1s-2s energy level difference. A positive result would give an unambiguous proof for CPT violation. Comparing the sensitivity of different observables ongoing experimental programs favour clearly a measurement of the ground state hyperfine splitting. Such an experiment is discussed by the ASACUSA experiment.

For precision experiments with antihydrogen statistics can be expected to be a limiting factor, once the production of the system has been optimized[9]. A $\overline{p}$ source of strength well beyond the CERN AD will thus be indispensable for this challenging physics.

8.4 Properties of the known basic interactions

8.4.1 Electromagnetism and fundamental constants

Accurate measurements of the electron magnetic g-factor and precise spectroscopic measurements in atomic hydrogen have played a crucial role for the development of modern physics, in particular of QED.

A precision determination of the electron magnetic anomaly using a single particle stored in a Penning trap yielded todays most precise value for α. Experimentally the difference of the cyclotron and the Larmor precession frequencies were measured, a technique known as a g-2 experiment.

Highly sophisticated laser spectroscopy experiments of the Lamb shift in atomic hydrogen are primarily sensitive to self energy terms and have reached a relative accuracy of order 10^{-6}. The limitation for the accuracy of calculations arises from the insufficient knowledge of proton

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[9] In fall 2002 both collaborations have reported the successful production of cold antihydrogen in a combined antiproton and positron charged particle trap.

structure parameters, e.g. the mean square proton charge radius r_p (figure 8.5). Hence, these measurements may be interpreted as a determination of the proton form factor at zero momentum transfer[10]. Because of the higher sensitivity of muonic atoms to nuclear shapes, a Lamb-shift type experiment in muonic hydrogen is presently being set up at PSI to obtain more directly and independently a 30 times improved value for r_p. This will allow a verification of highly precise bound state QED calculations in atomic hydrogen including three loop contributions in vacuum polarization .

Leptons can be considered structureless to dimensions down to 10^{-18}m. The interpretation of measurements in the muonium atom, the bound state of a μ^+ and an e^-, is therefore free of difficulties arising from the structure of its constituents. Thus QED predictions with two orders of magnitude higher accuracy than for the hydrogen atom are possible. The ground state hyperfine splitting as well as the $1s-2s$ energy difference have been precisely determined recently. These measurements can be interpreted as QED tests or alternatively - assuming the validity of QED- as independent measurements of α as well as of muon properties (muon mass m_μ and muon magnetic moment μ_μ). These experiments are statistics limited. Significantly improved values could be obtained at new intense muon sources.

There is a close connection between muonium spectroscopy and the determination of the muon magnetic anomaly a_μ. The precise fundamental constants are indispensable for the evaluation of the experimental results of a muon g-2 measurement series, which is presently progressing in a magnetic storage ring at the Brookhaven National Laboratory. A precision of 0.7 ppm has already been reached and the final goal is 0.4 ppm exploiting data recorded for muons with both signs of charge.

The muon magnetic anomaly arises from quantum effects and is mostly due to QED. However, there is a 58 ppm strong interaction contribution which arises from hadronic vacuum polarization. The influence of weak interactions amounts to 1.3 ppm. Whereas QED and weak effects can be calculated from first principles, the hadronic contribution needs to be evaluated through a dispersion relation and experimental input from e^+-e^- annihilation or hadronic τ-decays. Calculations of the hadronic part in a_μ depend on the choice of presently available experimental hadronic data. The results for a_μ differ by 3.0 respectively 1.6 standard deviations from the averaged experimental value. Intense theoretical and experimental efforts are needed to solve the hadronic correction puzzle, which also strongly relates to the running of the fine structure constant α_s.

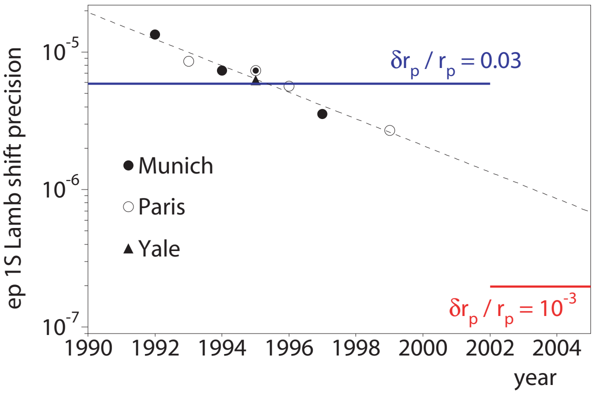

Figure 8.5: The expected development of accuracy in the determination of the ground state Lamb shift in hydrogen is confronted with the limit imposed by the present and the expected knowledge of the proton radius.

If a_μ is included in the fitting procedures for extracting the electroweak parameters from all relevant experiments in a consistent way, the most likely value for the Higgs mass is shifted significantly below the established lower experimental bounds. This indicates either a mistake in one of the input experiments or the present SM is insufficient to describe all experiments to date coherently. For the muon magnetic anomaly improvements both in theory and experiment are required, before a definite conclusion can be drawn whether a hint of physics beyond standard theory has been seen. The question whether the hadronic effects can

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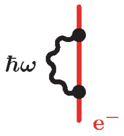
[10] Similarly the magnetic proton radius limits calculations of the hydrogen hyperfine structure some 6 orders of magnitude below present experimental values.

The Role of Quantum Electrodynamics among Fundamental Interactions

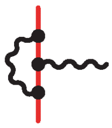
In the framework of the SM the electromagnetic interaction of electrically charged particles via a quantized electromagnetic field has a U(1) symmetry. Quantum Electrodynamics (QED) was the first available and it is the best confirmed quantum field theory in physics. Important concepts like renormalization were created along with the development of this framework. Rather different conceptual approaches must be applied for describing properties of free particles and scattering processes and for bound states.

The radiative corrections to the results obtained, e.g., from the Dirac equation include the emission and reabsorption of virtual field quanta (photons) and loops consisting of vertex corrections and vacuum polarization. The latter is the creation and annihilation of virtual particles. Retardation, recoil effects and in many electron systems the photon exchange between electrons need to be accounted for as well. Typical precision calculations include such processes and combinations thereof up to high orders. Feynman diagrams are graphical representations of mathematical prescriptions to account for such processes.



self energy

vacuum polarization



vertex correction

Due to the smallness of the fine structure constant α, which together with the electric charge of particles determines the strengths of interactions, perturbative treatment can lead to astounding accuracy. The deviation of a fermion magnetic g-factor from the value 2 in Dirac theory is known as the particles magnetic anomaly $a = (g-2)/2$, for which QED contributions to 4th order in α have been calculated completely. For atomic hydrogen the differences in level energies from Dirac theory values which are caused by QED effects are known as Lamb shifts. Here calculations are available up to 7th order in α. Such precision, which is possible in light systems, can be exploited to extract from accurate measurements the values of important fundamental constants such as α, the Rydberg constant, fundamental lepton masses, g-factors, magnetic moments and many more. The internal consistency of the theory and the basic underlying assumptions could also be verified in precision experiments. Among the most important of such tests are the existence of one single electric charge unit for all electromagnetically interacting systems and the good agreement between various values of α extracted from principally different experiments.

The accuracy in QED allows to observe also the influence of other but electromagnetic interactions in precision experiments such as measurements of level energies and magnetic anomalies. Even for purely leptonic systems the strong interaction plays an important role due to hadrons appearing in vacuum polarization loops. In bound states containing hadrons, i.e mesons, nucleons or larger atomic nuclei the inner structure and the dynamics of charge carrying constituents need to be taken into account. This often limits the precision reached in calculations.

The description of bound systems with nuclei with high charge numbers Z has by far not reached similar levels of accuracy. Even second order effects in α are still subject of present theoretical efforts. Further, the calculation of wave functions in many electron atoms and ions to better than percent accuracy presents a challenging problem; such precision is essential, e.g., for measurements of weak effects in atoms (see section 8.3.1).

For bound systems where $Z\alpha$ approaches (or even exceeds) unity we have a field theory with strong coupling with similarities to some problems encountered in QCD. This is an active field of research and non-perturbative methods such as lattice calculations may lead to satisfactory results. Of interest are possible yet unobserved phenomena in this strong coupling region associated with binding energies exceeding the mass of an electron-positron pair.

be understood well enough needs to be definitively answered before a new experiment should be considered. This could be performed with at least one order of magnitude improved precision using state of the art technology.

Exotic atoms are also well suited to test the vacuum polarization part of QED. The present precision of 9×10^{-4} can be improved by at least one order of magnitude with dedicated experiments using state of the art crystal spectrometers. Especially pionic atoms can be produced with high stop densities also in gaseous targets of lower Z. Light atoms are completely ionized during the initial steps of de-excitation and any disturbing influence of the electron shell is removed. There is a high potential for development for pion and muon experiments with the advent of stronger sources of slow pions and muons.

Hydrogen-like or few-electron systems with high nuclear charges Z permit to extend verifications of QED to investigations of higher-order QED contributions such as two photon exchange. Presently available ECR as well as EBIT technology will be used for detailed studies of QED effects in such systems at different institutions. In particular ion storage rings provide favorable conditions, where intense cooled beams of high-Z ions up to bare uranium are available. Very high precision has been reached in such experiments at GSI. Trapping of highly charged ions is being prepared. Beyond hydrogen-like systems, helium- and lithium-like heavy ions open a new window to explore the interplay of radiative corrections and relativistic electron correlation effects in strongly bound systems. They provide a testing ground for relativistic many-particle theories.

The magnetic g-factor of bound electrons in highly charged ions provides a further important test of bound-state QED in the strong coupling regime. In a high-precision Penning trap the g-factor of electrons bound in hydrogen-like ions can be determined through measurements of the cyclotron and the in this case three orders of magnitude higherLarmor frequency. Recent measurements yielded the g-factor of the electron bound in $^{12}C^{5+}$ with an accuracy of 5×10^{-10} in excellent agreement with a calculated value. The high experimental precision has allowed to extract from this the most precise electron charge to mass ratio. This experiment ranks among the most stringent tests of bound-state QED. Such experiments could be extended up to hydrogen-like uranium. Since the bound state electron magnetic anomalies exhibit sensitivity to nuclear properties particularly in heavy systems, new approaches to gain information about nuclei, such as polarizabilities, might open up.

Does α vary with time?

The idea that the fundamental constants, in particular α, may depend on time is about 65 years old and goes back to Dirac. Recent investigation of the fine structure doublets in quasar spectra indicate that α varies with time: $\dot{\alpha}/\alpha \simeq 10^{-15}$ year^{-1}. This conclusion disagrees with an upper limit derived from other arguments, and is criticized methodologically. Nonetheless, the problem certainly deserves serious experimental studies. The most direct check of $\dot{\alpha}/\alpha$ could be performed with atomic clocks. Other approaches might directly measure the ratio of (hyper-)fine and gross structure frequencies in cold atomic beams, trapped atoms or ions. For such experiments absolut frequency measurements must be improved by about two orders of magnitude compared to present possibilities. An other check is to compare the laboratory value of the ^{187}Re lifetime $\tau_{1/2}$(lab) with that inferred from the Re/Os ratio in ancient meteorites. This requires an improvement in accuracy of $\tau_{1/2}(\text{lab}) = 42.3(0.7)$ Gyr (68% C.L.).

8.4.2 Quantum chromodynamics

It is known that QCD (see Chapter 4) describes strong interaction processes well at high energies. At low energies a perturbative scheme is based on the concept of chiral perturbation theory (CHPT), which was extended to include baryons in the Heavy Baryon Chiral Perturbation Theory (HBChPT).

This approach works especially well at energies well below 1 GeV thus making exotic atoms especially suitable as a playground to test theoretical predictions. The most fundamental experiment in this respect is DIRAC (DImeson Relativistic Atom Complex) experiment at CERN, which aims at a measurement of the ground state width Γ_{1s} of the electromagnetic bound system $\pi^+\pi^-$. Γ_{1s} is proportional to $|a_0 - a_2|^2$ with a_0 and a_2 being the isoscalar and isotensor scattering lengths. The envisaged determination of $|a_0 - a_2|$ on the level of 5% meets the accuracy of the theoretical prediction. The experiment should be extended in future to a ground state shift measurement as well in order to disentangle the two different isospin contributions. Further developments should include a measurement of the πK system thus extending the study of chiral symmetry breaking to $SU(3)_L \times SU(3)_R$ symmetry breaking.

Whereas the DIRAC experiment delivers presently first data, the experiments at PSI dealing with the pionic hydrogen system have reached a high level of maturity. The isospin separated scattering lengths a^+ and a^- can be obtained by measuring the ground state shift $\propto a^+ + a^-$ and width $\propto |a^-|^2$ separately (see figure 8.6). These experiments can be considered as a test of a special chiral low energy theorem, in this case of the Weinberg-Tomozawa theorem. With a planned accuracy of about 10^{-2} for both shift and width, HBChPT can be tested to 4-th order perturbation expansion. The width yields a high precision determination of the πNN coupling constant. This allows then a refined check of the Goldberger Treiman relation and represents a further measurement of a low energy sum rule. A precise width measurement is very demanding as it requires a much better knowledge of accelerating effects in the pionic hydrogen system than presently available.

The investigation of the kaonic hydrogen atom has been pioneered at KEK in Japan and is presently being conducted at the DAΦNE storage ring in Italy. The 1% accuracy envisaged will permit a sensitive determination of the KN sigma term, which is a direct measure of the strangeness content of the proton.

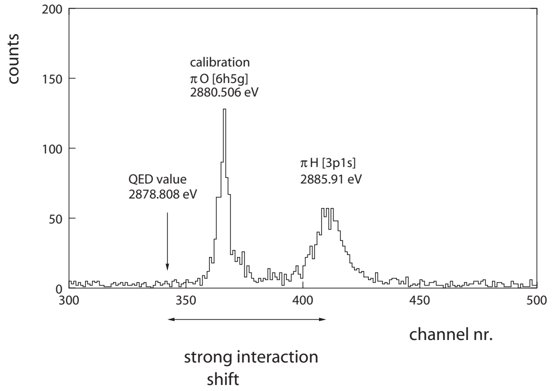


Figure 8.6: The pionic hydrogen 3-1 transition is shown together with the pionic oxygen 6-5 complex used for calibration.

8.4.3 Gravity

The universality of free fall i.e. the independence of gravitational interaction from the falling object's composition (the weak equivalence principle WEP) was tested for ordinary matter to a precision of one part in 10^{12} by Eötvös/Dicke experiments. The question whether antiparticles couple in the same way to gravity was never experimentally tested before (and experiments with elementary particles are scarce as well). An early attempt using charged antiprotons at the CERN Lear facility lead to the conclusion that systematics associated with the electromagnetic force completely obscure any gravitational effects and only neutral systems can provide sufficient accuracy.

Experiments in this direction are extremely difficult and would require long lived neutral particles. Antihydrogen would be a well suited candidate and the production of a sizeable number of very slow antihydrogen atoms would be the very first step into the direction of experiments testing the WEP also for antimatter. Most recent considerations concentrate on interferometric experiments in the spirit of the Colella-Overhauser-Werner experiments performed with neutrons. The ideal properties of the antihydrogen atom triggered an intense experimental effort at CERN/AD to combine positrons and antiprotons in traps. The experiments are extremely challenging and will require high flux

$\overline{p}$ sources.

The inverse square law of gravity appears to be valid from cosmical scales down to the 0.2 mm range. Superstring theories appear to be attractive candidates for a unified field theory of all fundamental interactions in compliance with quantum theory and relativity. Superstring or Membrane Theories may include Supersymmetry/Supergravity and the present Standard Model as low energy limits. The extra dimensions necessary to construct this framework are considered as rolled up and could give rise to deviations from Newton's gravitational law at small distances. Some models predict extra dimension radii in the nanometer range or even at subnuclear size. Besides precise measurements of Einstein's cosmological constant the search for extra dimensions is presently viewed as the most promising route to find hints to Superstring Theory where extra dimensions are a generic feature. Among others, experiments have been proposed to look, e.g. for graviton emission in high energy p-$\overline{p}$ collisions. It can be expected that this research field will experience a strong development. Nuclear physics will play a major role to investigate the femtometer scale or below.

8.5 Recommendations

We recommend that priority in support be given to resolve the central and intriguing questions in fundamental physics. The recommendations are based upon the available expertise and facilities in Europe. NuPECC's focus should be concentrated to provide state of the art possibilities to achieve the goals in the field. Both, the availability of skilled researchers in experiment and theory and the accessibility of adequate infrastructure are indispensable for investigating efficiently and successfully the central issues:

- **The nature of the neutrinos.** With the recent observations of neutrino flavour changes it will be important now to prove oscillations unambiguously by flavour appearance and by length/ energy dependence. Further determinations of parameters in neutrino oscillations are needed. Precise measurements of absolute neutrino masses are strongly recommended. The nature of neutrinos as Dirac or Majorana particles has to be addressed through neutrinoless double β-decay, where a worldwide concentration on the most promising approaches would be indicated.
- **Time reversal and CP violation.** A continuation of precise measurements of CP violation in the K^0 and B^0 system will reveal details of the effect and will lead towards a better understanding of its origin. Through the smallness of Standard Model CP violation in the D^0 system it offers strong possibilities to search for new physics. Searches for permanent electric dipole moments in different fundamental systems like electron, muon, neutron, nuclei and atoms are complementary and have a very high potential to discover new sources of CP violation which are needed in explanations of baryo- and lepto-genesis. Additional information can be obtained from searches for T-odd correlations in β-decay.
- **Rare and forbidden decays.** Baryon number, lepton number and lepton flavour violating processes such as $n \rightarrow \overline{n}$, neutrinoless double β-decay, $\mu \rightarrow e^+ \gamma$, $\mu^+ N \rightarrow e^+ N$, $\mu \rightarrow e^+ e^- e^+$ and $(\mu^+e^-) \rightarrow (\mu^-e^+)$, are excellently suited to constrain parameters in speculative models and to probe their validity, e.g. supersymmetry. Rare meson decays can yield important SM parameters.
- **Correlations in β-decay.** Precision measurements of momentum and spin correlations in nuclear, neutron and muon β-decays render the possibility to reveal non V-A contributions to weak processes.
- **The unitarity of the CKM matrix.** The presently not well satisfied unitarity condition for the CKM matrix presents a puzzle in which the correctness of experiments as well as the theoretical assumptions are at stake.
- **Parity non-conservation in atoms and ions.** Parity non-conservation in atoms can be studied more thoroughly in radioactive species of, e.g., Cs, Fr and Ra, where a

particular potential to discover New Physics exists, e.g. leptoquarks. Improvements in atomic physics calculations of many electron atoms will be crucial. Measurements using highly charged ions are expected to be less hindered by atomic structure calculations.

- **CPT conservation.** Precision experiments in a variety of fields in physics will lead to improved limits on or discoveries of the violation of Lorentz and CPT invariance.
- **Precision studies within the Standard Model.** Exotic atom spectroscopy provides important input for the further development of low energy QCD. QED bound systems can deliver most precise values of fundamental constants. Weak interaction in electron nucleus scattering provides precise information on nucleon structure and can deliver neutron distributions in nuclei and new physics. Weak interaction experiments in atoms are well suited to probe anapole moments and nuclear structure effects.
- **Gravity and time variation of constants.** Deviations of the gravitational force from the Newtonian law are predicted in theories with extra dimensions. Effects could be expected at sub-millimeter, even at atomic and nuclear length scales. A time variation of the strength of the electromagnetic interaction might have been seen in astronomical observations. Precision experiments could here make significant and decisive contributions towards novel approaches for an all encompassing description of space time as attempted in string theory.

In order to achieve the outlined challenging physics goals the European nuclear physics community needs an appropriate environment consisting of adequate academic positions for young researchers and state of the art facilities. These comprise centrally:

- **Theoretical support; positions at universities.** The constantly improving technology allows for an ever increasing number of possibilities for experiments. In order to exploit these successfully and in order to concentrate on the important issues well founded theoretical guidance is indispensable. This requires a sufficient number of skilled theorists located at universities. At the same time it must be assured that a sufficient plurality of experimental positions is maintained.
- **High power proton driver; target research.** A large number of possible experiments would benefit from the availability of an intense proton driver in Europe with several MW beam energy. In this connection the power compatibility of targets is extremely important and corresponding research and development should be carried out with highest priority. Such a proton machine could serve as a core for a neutrino factory, an antiproton facility, a muon factory, a neutron spallation source and an advanced ISOL facility. Most of the covered research topics in this chapter will benefit from such a machine.
- **Cold and Ultracold Neutrons.** New and improved neutron sources with high fluxes of cold and high densities of ultracold neutrons will boost fundamental neutron physics.
- **Low energy radioactive beams.** The availability of radioactive beams at low energies is a prerequisite for precision studies of weak interactions in nuclei and atoms. More dedicated facilities with sufficient beam time for systematic studies in precision experiments are needed.
- **Improved trapping facilities.** The advances in modern charged particle and neutral atom trapping need to be transferred to radioactive beam facilities. In particular the ongoing efforts for efficient slowing down and trapping of systems of interest should be coordinated worldwide to obtain optimal and most precise results on low energy electroweak phenomena and accurate values of important parameters like masses and g-factors.
- **Underground facilities.** The continuation of the availabilities of underground laboratories is a prerequisite for investigations of

the solar neutrinos and the search for neutrinoless double beta decay. The development of low background techniques is a standard method of this kind of experiments as well as of other very rare event searches.

Provided these points will be met, a productive future for fundamental interaction research at nuclear physics facilities with a richness of new fundamental results can be expected in the coming 15 years. In particular, the foundations of physical processes can be expected to be significantly deepened.

9. Applications of Nuclear Science

This chapter was written by D. Guerreau (NuPECC), T.Calligaro (France), C. Cohen (France), H.J. Körner (Germany)[1], G. Kraft (Germany), P. Mandò (Italy), G. Raisbeck (France), J.P.Schapira (France)

Basic research in nuclear and particle physics requires the development of new experimental techniques suited to investigate atomic nuclei and sub-nuclear particles, and to measure their properties. These techniques are being used extensively for studies in neighbouring areas of the natural sciences and in medical applications. Such applications have been described in a recent NuPECC report published in 2002 (Nuclear Science in Europe: Impact, Applications, Interactions; hereafter referred to as 2002 Report. See http://www.nupecc.org/pub). This report reviewed the recent progress made in the fields of Energy, Life Sciences, and Atomic and Condensed Matter Physics. Applications of nuclear science are so numerous that an exhaustive review cannot be given here. The sphere of competence involved by the applications of nuclear physics is extremely wide as it includes disciplines far apart from each other. They span from life sciences and medicine to humanistic disciplines like art-history, history itself and archaeology (Box 1), to environmental sciences (Box 2), to other disciplines and technological or industrial fields like energy. It also includes the field of civil security and humanitarian problems like contraband detection, anti-terrorism and de-mining. Most of these applications require the identification of detailed material structure, very often at a very high level of sensitivity. The two most relevant methods are AMS (accelerator mass spectrometry) and IBA (ion-beam analysis, which includes different techniques such as PIXE, RBS, NRA...).

The key-role played by the Nuclear Physics based facilities in Europe has to be mentioned here. The large variety of available particles and ions ranging in energy from eV to GeV and the powerful equipment at the disposal of scientists from different disciplines strongly benefit applications. A Handbook on Interdisciplinary Use of European Nuclear Physics Facilities will be soon published. It will describe the equipment for interdisciplinary and industrial applications available at 24 Nuclear Physics Laboratories all over Europe.

In the following, the reader will find a summary of the 2002 Report. The convenors of the three working groups on Energy, Life Sciences and Atomic and Condensed Matter Physics have been asked to present the results that emerged from their respective areas (all relevant references and the sources of the figures are given in the 2002 Report).

9.1 Life sciences

At the grand old European universities science, especially physics, emerged from the medical faculties, because medical science was necessary and stimulated the research on the underlying processes in physics, chemistry and biology. Today, physic research has a value of its own, but scientific progress is the basis of the high living standard in the developed countries including a better medical care. In addition to this more general connection, there still exists a close interaction on a deeper level between life sciences, medicine and physics. This is especially true for nuclear physics and life sciences where many techniques and results of nuclear research have been adopted to their applications in biology and medicine. It is also true on the level of the exchange of ideas and may be more important on the exchange of people. Famous physicists have changed to biology or medicine like

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[1] † (7. September 2003)

Max Delbrück or have contributed to the thinking in life science like Erwin Schrödinger in his famous book: “What is life?”. There he applied the thinking of quantum mechanics to biology and formulated for the first time the quantity of a biological gene as a chemical entity of a biomolecule. His estimations were based on observations in radiation biology where cellular functions were inactivated by the exposure to beams of X-rays and particles and he found the average size of a gene within reasonable errors. It was the influence of Schrödinger’s book that played an important role on the final evaluation of the molecular structure of the DNA by Watson and Crick.

In the opposite direction, i. e. from the applications to basic research, the interest generated by the discovery of the X-rays by W.C. Röntgen can be noted. The primary publication on this new type of radiation in proceedings of the Würzburg medical-physical society would not have attracted so much attention without the parallel publication of the first X-ray image of the hand of Röntgen’s wife. Immediately X-rays were used as a diagnostic tool all over the world and stimulated the physics research to understand the physical nature of the medically helpful X-rays.

The discovery of natural and artificial radioactivity by Becquerel and the Curies was not paralleled by the application of isotopes in life science in the same way as for the Röntgen innovation, because the production of the radioactivity was initially too expensive to become a common tool. These applications spread later when the production of isotopes became available at the first nuclear accelerators, the cyclotrons at Berkeley and later on at nuclear reactors. The real breakthrough for these techniques came after World War II, when the explosion of the atomic bombs in Hiroshima and Nagasaki and their consequences motivated the search for and the use of nuclear applications for peace on a large scale. Today, nuclear diagnostic tools are established in medicine and a new discipline has developed, the nuclear medicine. In therapy of cancer patients, the high-energy particle accelerators originally developed for nuclear research became an important tool for the cure of deep seated and inoperable tumours. For these two medical applications two different properties of particles are used: The high efficiency in detecting the decay of radioactive isotopes was important for the diagnosis whereas for the therapy it was the enhanced biological effect caused by the large energy deposition in the tracks of single ions.

In nuclear medicine the radioactive isotopes of iodine or fluorine are frequently used to label biologically active compounds that can be followed in their path through the human body. Meanwhile for each organ a specific drug has been synthesised that allows to measure its functions like secretion, blood flow etc.. The detection methods to produce an image of the isotope-distribution inside the body are a one-to-one translation from nuclear techniques. In the case of SinglePhoton Emission Computer Tomography (SPECT), collimators with one or many holes coupled to position-sensitive detectors produce an image with a resolution sufficient to acquire the medical information. Drugs labelled with positron emitters do not need collimators but use the coincidence condition of the two back-to-back simultaneously emitted photons to reconstruct an image from the signals measured in a ring detector around the patient. This Positron Emission Tomography (PET) is very efficient and can be used to detect small tumors because of its good sensitivity. But PET became also a tool to study brain functions of healthy test persons. Using fluorine labeled desoxy glucose (FDG) it is possible to differentiate between active and inactive brain areas and to see in real time the brain working. These studies have been very useful in brain research but meanwhile the Nuclear Magnetic Resonance (NMR) imaging has reached a sensitivity that allows the same studies without radioactivity. In NMR the hyperfine splitting of hydrogen in a strong magnetic field is measured in the absorption of the corresponding radio-frequency. The hydrogen distribution and the chemical environment around the hydrogen atoms can be monitored from the absorption pattern and the decay of the signal in time, respectively. NMR is another technique that emerged from nuclear research and will be the future technique for imaging and function testing of organs.

In the therapy of deep-seated tumours, ^{60}Co produced in nuclear reactor was first used to replace the low-energy photons from X-ray machines, because the Co gamma rays had a much better depth-dose distribution, that allowed to spare the skin to a large extent. Later higher-energy bremsstrahlungs photons from electron linacs replaced the cobalt units.

Today, charged particles like protons or heavier ions, e.g. carbon ions, represent the ultimate tool for tumour therapy of deep-seated and inoperable tumours (Figure 9.1).

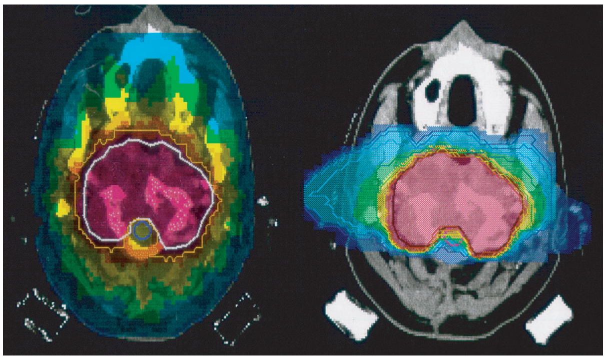

Figure 9.1: Comparison of photon(left) and carbon ion treatment plan of a base of the skull. The higher precision and the better sparing of the ion treatment are clearly visible.

Ion beams have an inverse depth-dose profile with an increase of the dose with increasing penetration depth up to a maximum at the end of the particle range. This guarantees a much higher dose in the target volume than conventionally possible and a greater precision of the dose delivery. In addition, carbon ions have a very favourable radiobiological behaviour. In the entrance channel at low dose mostly repairable damage is produced in the healthy tissue. But at the end of the range, in the high-dose area the amount of irreparable damage increases causing a greater effectiveness in killing the tumour cells. Clinical trials using carbon beams at Chiba, Japan and Darmstadt, Germany confirmed this radiobiological promise and resulted in clinical cure rates beyond any other therapy. Consequently, an increasing number of dedicated carbon-therapy medical centres are presently planned and in preparation in Europe and Japan. These centres are, with approximate cost of 100 MEuro, the largest single investments in medicine but the very positive clinical results seem to justify these large investments.

In biology, the use of radioactive tracers was pioneered by G. de Hevesy, first with natural radioactive isotopes later on with short-lived artificial isotopes. The tracer technique is the same as in the later developed nuclear medicine: a biological active molecule is labeled with a radioactive marker and followed by the detection of the radioactive decay. In this way many important biological pathways have been studied like the photosynthesis in plants. But also small amounts of important molecules like DNA can be detected after their separation by gel electrophoresis or other methods. DNA sequencing and protein analysis were not possible without the application of radioactive isotopes. The list of these very important and successful applications of nuclear techniques and products in biology can be complemented by many other examples like the radio-carbon method for dating of old, sometimes prehistoric material, accelerator mass spectroscopy and other applications in material research and industry.

In spite of these many positive aspects, nuclear science and research have to tolerate the deep public distrust because of the direct nuclear effects on people resulting from the Hiroshima and Nagasaki bombs or the Chernobyl and other accidents. In case of the atomic bombs it was the first direct confrontation of people with a nuclear interaction that is many orders of magnitude stronger than gravitation and electromagnetic power our normally experienced forces. The direct impact of an atomic bomb in form of heat and pressure created damage many orders of magnitude larger than the conventional but still terrible weapons. Immediately after the atomic bombing many people died from the radiation syndrome within the following 30 days. 15-20 years after the bombing, an increase of cancer incidence was observed of a few hundred additional cancer patients among the hundred thousand bomb survivors. These tragic events with their unexpected consequences were the turning point for an intensified radiobiological research, first in form of more epidemiological studies. Later on, when DNA structure was analysed and the culture mammalian cells were established the radiobiological research was able to study the mechanism of the biological action on ionising radiation like X-rays or high-energy nuclear particles.

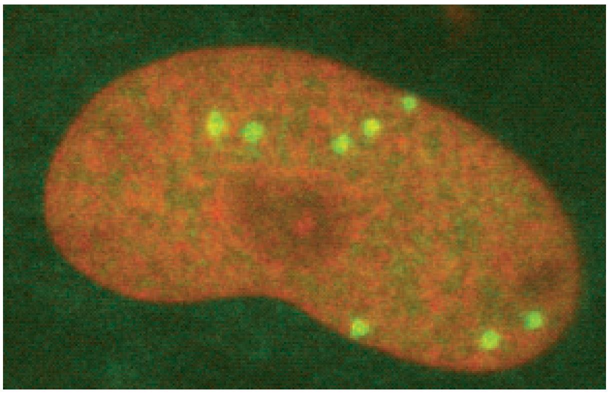

Figure 9.2: Image of a cell nucleus hit by eight heavy particles. The DNA is stained by a red-fluorescent dye. The yellow spots indicate particle traversals where a protein p21 accumulates that is involved in the recognition and repair of DNA damage.

From these studies the immediate consequences of a total body irradiation could be explained as the fast response of the most critical stem cell as well as the long-term effects of carcinogenesis and genetic mutation as very rare events. Accelerator experiments at nuclear research machines enlarged this knowledge to particle radiation and made the very efficient tumour therapy possible. In addition, first guidelines for the exposure of astronauts to the particles from cosmic radiation could be established. This radiobiological research is not at an end. The deeper understanding of molecular biology combined with the now achieved micrometer precision of particle beams from nuclear research accelerators starts a new period of radiobiological research. The vision of nano-beam technology applied to microbiology promises again new insights in life sciences covering many open questions (Figure 9.2).

9.2 Energy

Today, energy production throughout the world is facing a number of issues related to the expected increase in energy needs during this century, especially in the developing countries. Two important questions, i.e. resources preservation and environmental impacts (especially those related to climate change), can largely be answered by a significant use of nuclear fission as a source of energy. Moreover, beside its traditional application to electricity generation, nuclear energy might also play in the future an important role in the production of heat at high temperature (above 800 ˚C) for various industrial applications. In relation to these issues, one can identify at least two lines of research pursued by the Nuclear Science and Technology community. The first one deals with the reduction by transmutation of the long-term impact of the nuclear wastes produced in the present light-water reactors (LWRs) based on enriched uranium or mixed oxide plutonium/uranium fuels. The second one concerns the study of complete new types of reactors, belonging to the so-called Generation 41. Among these the use of a molten salt reactor based on thorium could be an answer to the aim of strongly reducing the long-term radiotoxicity of the highly active wastes while at the same time valorising the natural thorium resources by converting the present large amounts of plutonium into uranium-233. It also includes high-temperature gas-cooled reactors, which could lead to very innovative applications such as hydrogen production or water desalination. All these considerations concern nuclear-fission energy. On the other hand, nuclear fusion is presently at a research stage with the ITER project based on magnetic-confinement fusion (MCF). There is also some basic research carried out on an alternative technique using heavy-ions inertial-confinement fusion (ICF) with much less funding.

The contributions of the nuclear physics community in the field of transmutation, as well as activities concerning ICF have been described in two previous NuPECC reports (1994, 2002) dedicated to the Impact and Applications of Nuclear Science in the field of Energy. Concerning transmutation, the activities will very likely continue to focus on the so-called accelerator-driven systems (ADS), which seem to be best suited for the transmutation of some long-lived and highly radiotoxic radionuclides present inside spent nuclear fuels unloaded from reactors (see the schematic view in Figure 9.3).

Historically, in the beginning of the 90s when nuclear waste became a burning issue, nuclear physicists like C.D. Bowman in Los Alamos and C. Rubbia at CERN revived some ideas developed in various American and Canadian laboratories since 1952 to use high intensity accelerators in the nuclear energy field, especially for transmutation. These activities have led to the proposal of using a sub-critical reactor to burn large quantities of actinides presently produced in commercial LWRs. The neutrons needed to drive such a burner are produced inside a so-called neutron spallation target bombarded by a proton beam from a high power accelerator (typically 1 to a few 10 MW). Because the nuclear and high-energy physics communities are very familiar with these two components (accelerator and spallation target) as well as with the related Monte-Carlo computing techniques, they bring in a major and specific contribution to the studies of such an ADS as well as on related nuclear-data acquisition. [1]

Worldwide, most of the studies related to transmutation deal almost exclusively with ADS and with the development of advanced fuels and fuel processing methods related to ADS (e.g. inert matrix, pyrochemistry). Recently, increased efforts in the nuclear energy sector are observed in the US, in Japan (OMEGA project, especially the joint KEK-JAERI accelerator project) and in the European Community as it will be discussed now in more detail.

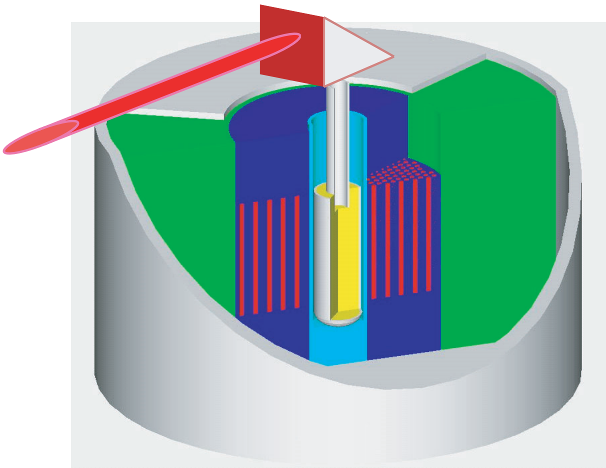

Figure 9.3: Schematic view of an accelerator-driven system (ADS) showing the beam pipes starting from the left (red pipe) and ending at the spallation target (yellow region). The fissile material is indicated by the red rods surrounding the spallation target.

There is an increasing support from the European Union for transmutation and ADS through the Nuclear Fission Action of the EURATOM programmes. Although modest, the funding allocated to partitioning and transmutation has been steadily increasing within the successive Framework Programmes (FP). It represents 24 MEuroon a total of 142 MEurofor Nuclear Fission in the present 5th FP, and may range between 30-35 MEurofor the next 6th FP under finalisation (2004-2008). It is worthwhile to point out the collaboration between research institutions and industrial partners such as Framatome or Ansaldo, making use of the valuable synergies in some of the 5th FP programmes dealing with the ADS subsystems and nuclear data (see the list in Table 9.1). These programmes, conducted within a laboratories network called ADOPT (Advanced Options for Partitioning and Transmutation), are in support of the Preliminary Design Studies for an Experimental ADS (PDS-XADS). By Spring 2004, ADOPT might become the transmutation integrated project of the 6th FP. The main goal of these activities is to establish the feasibility and the technical options for a 100 MW(th) European demonstration facility (XADS or Experimental ADS) by 2008, at the end of the 6th FP, in accordance with the recommendation of the April 2001 report issued by the European

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[1] Nuclear reactors are usually categorized in 4 generations. The first two include early and present reactors (LWR belong to Generation 2). Advanced reactors derived from the present one belong to Generation 3 (the only one in operation is in Japan), whereas complete new concepts (six have recently been selected by an international forum set up at the initiative of the US Department of Energy) belong to Generation 4.

Table 9.1: Transmutation part (24 MEuro) of the (P&T) programme (28 MEuro) of the 5th EU FWP.

Acronym	Research area	Coordinator	Number of partners	Length (month)	EU funding (MEuro)
Basic studies					
MUSE	Experiments for Sub-critical Neutronics Validation	CEA (France)	13	36	2.0
HINDAS	High and Intermediate Energy Nuclear Data for ADS	UCL (Belgium)	16	36	2.1
n-TOF-ND-ADS	ADS Nuclear Data	CERN	18	36	2.4
Technological Support					
SPIRE	Effects of Neutron and Proton Irradiation in Steels	CEA (France)	10	48	2.3
TECLA	Materials and Thermo-hydraulics for Lead Alloys	ENEA (Italy)	16	36	2.5
MEGAPIE	Megawatt Pilot Experiment	FZK (Germany)	16	36	2.43
Fuels					
CONFIRM	Uranium Free Nitride Fuel Irradiation and Modeling	KTH (Sweden)	7	48	1.0
THORIUM CYCLE	Development of Thorium Cycle for PWR and ADS	NRG (NL)	7	48	1.2
FUTURE	Fuel for Transmutation of Transuranic Elements	CEA (France)	10	36	1.7
Transversal projects					
ADOPT	Thematic Network on Advanced Options for P&T	SCK.CEN (Belgium)	16	36	0.4
PDS-XADS	Preliminary Design Studies of an Experimental ADS	Framatome (France)	26	36	6.0

Technical Working Group set up under the chairmanship of C. Rubbia. The Belgian project MYRRHA might be the starting point of such a demonstrator.

Beside this European effort, one must mention the ENEA programme around the TRADE experiment proposed by C. Rubbia. It consists in the coupling of a proton cyclotron beam (around 100 kW) to a spallation target installed in the central region of the TRIGA reactor of Casaccia (Italy) scrammed to sub-criticality. The aim of this facility is to test the ADS concept, especially the core physics, at a significant power level, intermediate between the MUSE experiment at MASURCA and the full demonstrator discussed above. The full-power operation is scheduled between mid-2007 and 2009.

The two other lines of research are related to complete new reactor concepts which have been included in the 6th FP under two headings: innovative concepts belonging to the nuclear technology domain (50 MEuro) and concepts producing less wastes belonging to the nuclear waste domain (90 MEuro). Within these two domains, a very modest effort costing between 10 and 20 MEuro is foreseen. At this stage of scientific feasibility, only basic studies can be envisaged within the nuclear physics community. This is the case, for example, for the use of thorium in an epithermal-neutron molten-salt reactor, which is studied at Grenoble. Various aspects are addressed: system studies aiming at simplifying the integrated fuel cycle, integral neutron cross-section measurements on various elements like lithium, fluorine, thorium, and several scenario studies.

To conclude this overview, on can make the following observations. In the early days of nuclear-energy development, neutronic and reactor physics were just one branch of nuclear science just as nuclear and particle physics or radiochemistry. Since then, these branches have gained more and more autonomy with respect to each other due to their increased technical complexity and specialisation. As a consequence, differentiated scientific and technical communities have emerged with their own culture and scientific approaches. Moreover, the nuclear-energy community was, and still is, in charge of developing peaceful as well as military applications of nuclear energy and became therefore more and more linked to technical, industrial and strategic issues. On the other side, the academic world, i.e. universities, national and international research organisations (e.g. CERN at a European level), has been dealing almost exclusively with fundamental nuclear science and related techniques such as accelerators. But since the beginning of the 90's, there is a comeback of this community into the field of nuclear energy, essentially through the nuclear waste issue. It is now acknowledged that transmutation with ADS and innovative concepts may largely profit from its specific expertise, provided a tight collaboration between nuclear physics, reactor physics and material sciences takes place.

9.3 Interactions between nuclear, atomic and condensed matter physics.

Nuclear Physics interacts with numerous other scientific fields. The particularly fertile interactions with Atomic and Condensed Matter Physics have been presented in length in one chapter of the very recent NuPECC 2002 Report "Nuclear Science in Europe: Impact, Applications, Interactions". In what follows, we only intend to introduce briefly the main points, at the intersection of the three disciplines, on which recent efforts have focused and where important progress has been achieved.

Of course nowadays and since long, Atomic and Condensed Matter Physics use rather extensively and routinely instruments that were first developed in the context of Nuclear Physics. This is the case in particular for implantors, small accelerators and for synchrotron radiation. Such facilities are now available in environments independent of Nuclear Physics and the very important and versatile results that they provide are not within the scope of our short presentation. We want here to concentrate on research domains where scientists of the three disciplines exchange. These exchanges may concern basic concepts, but may also be related to instruments and techniques. Many efforts at the borderlines between nuclear, atomic and solid state physics have triggered in the past many important discoveries. The close collaboration between the different disciplines at accelerator laboratories (for example at ISOLDE/CERN, GANIL/Caen, GSI/Darmstadt) does not only result in an efficient use of modern accelerator facilities but also in substantial progress in physics which could not be reached without it.

An important field of research, in which Nuclear Physics or Nuclear Physics methods are used to answer usually addressed questions, is the field of High Energy Physics. This approach implies the use of highly developed experimental techniques that allow access to supplementary information or even to gain complementary results in addressing questions of fundamental interest. Depending on the types of experiments and the information gained, they can be subdivided in two classes. In the first class of experiments, it is tried to extend the present knowledge within the frame of the Standard Model as much as possible, thus testing the predictive power to its ultimate limits. Here, one finds all the experiments which are presently being set up to test quantum electrodynamics (QED) and quantum chromodynamics (QCD) at their limits; in other words experiments that go to increasingly higher orders in a perturbation series. QCD can nowadays be included here since recently a powerful theoretical tool has been developed (chiral perturbation theory and heavy-baryon chiral perturbation theory) which permits perturbation calculations. An illustrative example relates to high-precision measurements of QED in bound states of high-Z hydrogen-like atoms (Lamb-shift and g-factor measurements). A second example is the investigation of strong interaction phenomena in elementary hadronic atoms like pionium or pionic as well as kaonic hydrogen. Both experimental programs have in common that they are conducted with two-body

Ion Beam Analysis:
An application to art and archaeology

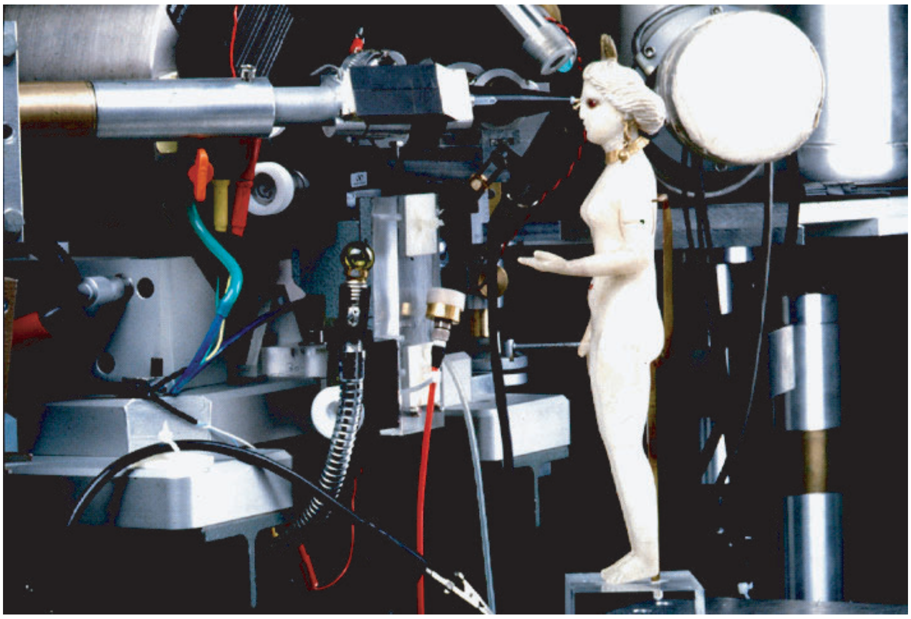
For almost 15 years, an IBA facility called AGLAE (Accélérateur Grand Louvre pour l'Analyse Elementaire) has been installed in the Centre for Research and Restoration of the Museums of France, in the Louvre museum. A special set-up, namely an external beam line, has been developed for the in-air analysis of large or fragile works of art without sampling. This facility is used for both short investigations at the request of museum curators and extensive research works in art history, archaeology and conservation science.

One type of applications is related to materials identification. The identification of constituent materials of art works is the basic objective of any scientific study. It yields important information on the applied artistic techniques and the authentication of artworks. This task can be easily carried out by external beam PIXE (Particle-Induced X-ray Emission). Such an approach is illustrated by numerous studies on papyri, manuscripts, miniatures and drawings, the aim of which is to determine the nature of inks, pigments or metal points.

This technique was applied to a set of drawings by Pisanello, a famous Italian Renaissance artist. It was shown that the artist used several types of metal points: lead or silver-mercury alloy on parchment or paper without preparation and pure silver on a preparation based on bone white or calcium carbonate. Another study has been devoted to the identification of pigments used in medieval illuminated manuscripts, kept in the National Library of France.

Concerning Egyptian papyri, the palette of the Book of the Dead from the Middle Empire has been investigated. Macroscopic distribution maps of elements have permitted to identify the different pigments: red (hematite, ochre), black (carbon), yellow (orpiment) and white (huntite). A light blue pigment containing strontium (celestite) has been revealed for the first time.

Another example of mineral identification stems from the study of a Parthian statuette kept in the Louvre and representing the goddess Ishtar. The red inlays representing the eyes and navel turned out to be rubies and not coloured glass as previously thought. In effect, the PIXE spectrum of major elements indicates the presence of aluminium and chromium, characteristic of ruby.



T.Calligaro *et al*, J.Nucl.Instr. and Meth. B 161(2000)328.

systems thus avoiding many-body effects, which would render high-precision experiments impossible.

On the other hand, there is a common belief that the Standard Model cannot be the end of the story because of several reasons; e.g., it has too many free parameters. Much effort therefore goes into the search for physics beyond the Standard Model. Neutrino experiments and weak-interaction studies in neutron and nuclear decay find their motivation in this search. Here, one deals with simple systems, like neutral particles or atoms in a trap, which permit a clean theoretical treatment and can be studied with utmost precision experimentally. This "precision frontier" is, in many cases, equivalent to interaction energies barely achievable with accelerators and allows a glance to cosmological times at which, to our present understanding, symmetry was broken. Good examples are the search for the electric dipole moment of the neutron or β-decay correlation experiments with neutrons or trapped atoms. Also, the use of nuclear-physics techniques for the study of highly ionised atoms or exotic atoms opens many possibilities for high-precision experiments to address physics beyond the Standard Model. Examples are the search for right-handed currents in weak decays or the search for violation of conservation laws like charge-parity (CP) or charge-parity and time reversal (CPT).

Nuclear properties are also currently studied with techniques related to Atomic or Condensed Matter Physics. Such techniques are applied in order to obtain model-independent information on nuclear ground-state properties of short-lived nuclides such as atomic masses, half-lives, nuclear spins, magnetic dipole moments, electric quadrupole moments and nuclear charge radii. Information is also obtained on excited states of nuclear matter; e.g., study of internal conversion via bound atomic states and search by ion blocking for the influence of nuclear dissipation on fission times. Laser ionisation and polarisation as well as beam cooling techniques, developed by atomic physicists, are now being applied at facilities for nuclear physics.

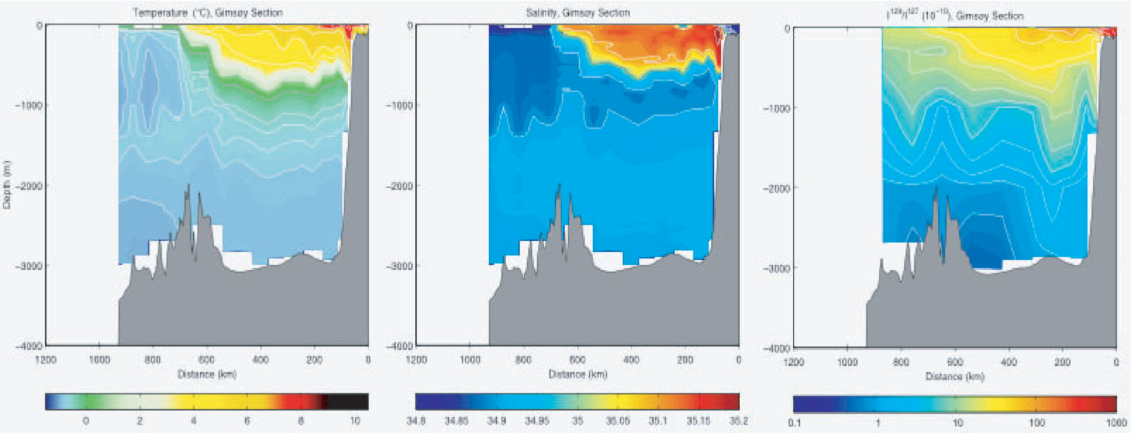
Accelerator techniques being motivated by nuclear physics are used in order to create unusual atomic systems such as muonic atoms, highly charged ions or anti-hydrogen which allow one to study atomic physics under very extreme or unusual conditions. For example, the elements heavier than uranium up to the so-called superheavy elements can only be produced artificially at accelerators or nuclear reactors. These heavy elements are testing grounds for relativistic effects in atomic physics and chemistry. Also, the long isotopic chains accessible at radioactive ion beam facilities (on-line isotope separator or in-flight facilities) enabled to explore a large range of mass numbers and in this way provided a stringent test of the theory of isotope shift consisting of a volume and a mass effect.

The availability of high-performance ion storage rings of swift ions, of cluster accelerators producing intense beams with excellent optical quality and of ion sources providing highly charged slow ions, have enabled a series of benchmark experiments on particle-matter collisions. In addition, developments in target preparation techniques along with significant advances in large area many-particle detection devices of extreme spatial and time resolution have allowed to study in detail the dynamics of collision products. The whole research activity in this field covers a wide range of scientific topics: New generation of prominent experiments concerns the interaction of atomic, molecular or cluster ions, over a wide range of energy (from eV to GeV), with matter-matter including namely electrons, plasmas, atoms, molecules, clusters and solids. Nowadays, in many cases, both the states of these incoming ions and the response of the target are characterised during the collision. The fundamental goal in many of these studies is to probe the response of matter under the influence of strong and short pulses of electromagnetic radiation.

For collisions with dilute media, high-precision measurements cross sections of multiple processes are at hand and reveal shortcomings of the most sophisticated theories. Nevertheless, the knowledge acquired on elementary process has opened the way to the investigation of the dynamics of more complex systems,

Accelerator Mass Spectrometry (AMS): One application to environmental studies

One of the most pressing current environmental questions is that of climate change. A hot subject is what type of mechanism might lead to dramatic climate changes on time scales as short as several decades which are now recognised as having occurred in the past (see for example, Physics Today, August, 2003)? Such studies can be made observing modifications of ocean circulation patterns in the Nordic seas where deep-water formation is an integral driving force for global ocean circulation. A new tool to trace these patterns is ^{129}I (discharged in substantial quantities by the nuclear fuel reprocessing facilities at La Hague (F) and Sellafield (UK) into the English Channel and Irish Sea, respectively). Because of its long half-life (15.7 My), ^{129}I is not considered to be a radiological hazard. On the other hand, its solubility, its unique temporal and spatial input function and the great sensitivity to measure it by AMS makes it a particularly attractive tracer for this region. One requirement for such studies is a simple, rapid and inexpensive procedure for preparing and analysing the large number of seawater samples, which are needed for oceanographic applications. An example of such measurements is given in the Figure, which shows the distribution of ^{129}I, relative to the stable isotope ^{127}I, together with temperature and salinity, as a function of depth and distance from the coast, for a cross section perpendicular to the Norwegian coast, at ∼ 70 ° latitude. The Figure represents several hundred analyses made on the Gif-sur-Yvette AMS facility, on samples prepared from only 100 ml of seawater. It shows the very strong concentration of ^{129}I in the Norwegian Coastal Current, as well as its degree of spreading into the warmer and more saline Atlantic Current (the famous Gulf Stream), as it prepares to enter the Arctic Seas. An added environmental benefit of these studies is that they can predict the fate of various other pollutants, which enter the North Sea via several European rivers and then are transported into the ecologically sensitive region of the Arctic Seas.



Potential temperature (˚C), salinity (psu) and ^{129}I/^{127}I ratio (10-10) in seawater as a function of depth and distance perpendicular to the Norwegian coastline at ∼70 ˚C N latitude. (J.-C. Gascard *et al.*, submitted to Geophys. Res. Lett.)

like induced fragmentation of molecules or clusters. Ions interaction with electrons shows up new states of atoms, molecules and clusters. Beside the prime importance of electron-ion collisions in plasmas directly related to heavy-ion inertial-fusion purposes, resonances in collision cross sections provide today an alternative access to highly accurate information on atomic energy levels, and therefore a sensitive test of QED calculations. Finally, mechanisms responsible for strong energy deposition during ion interaction with condensed matter (bulk and surface) are determined with deep insight. These studies clearly provide crucial information for the understanding of the first stages of material modifications. Among them, the development of experiments related to spectacular charge-exchange processes taking place during the interaction of slow highly charged heavy ions with surfaces should be emphasised.

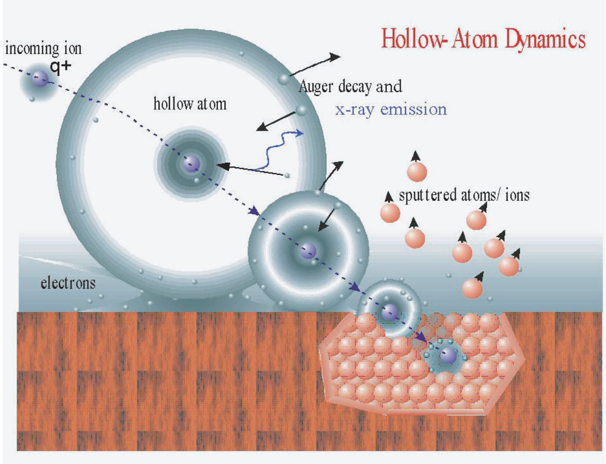


Figure 9.4: An artist's view of processes induced by the approach of a highly charged ion to a surface.

Beyond its own fundamental interest, the field of ion-matter interaction has also a strong impact on many other scientific domains like Astrophysics and Astrochemistry, Atmospheric Physics, Radiobiology and Radiation Chemistry.

Material modification induced by irradiation is a scientific domain at the frontier of several disciplines (Figure 9.4): Nuclear Physics, Atomic Physic, Solid State Physic and Chemistry. One prominent fact of this science is the variety of the materials studied, ranging from metals to living cells and the variety of projectiles and energies used (photons, electrons, neutrons and ions in the eV to GeV energy range). The other important characteristic is the constant interplay between the applied and basic fields. In the applied field, materials are submitted to irradiation in the nuclear-energy industry, in space and in microelectronic industry. The knowledge and understanding of the detrimental effects induced by irradiation is a clear need. The emphasis on the fission fragment damage is boosted by the eventuality of transmutation of actinides in order to reduce the problem of the nuclear-waste management. As radiation induces non-equilibrium states of matter, new materials can be created with novel properties. In industry, many applications of material irradiation have been developed for the production of micro- and nano-materials of high technological interest. Recent developments are on replica or template techniques that allow the production of cylindrical objects of micrometer-nanometer size of virtually any material on any surface. Another example is the production of nanopores by chemical etching of ion tracks.

In basic research, radiation is a means, sometimes unique, to induce non-equilibrium states of matter. In this sense, it is an interesting subject of physics by itself. In the last 15 years, a sizeable scientific community of solid-state scientists has used facilities shared with nuclear physicists or originally devoted to nuclear-science studies. The interest of this community is on the highly excited states of matter induced by swift heavy ions, SHI, high or low energy clusters beams and very low velocity highly charged ions, HCI. These ion beams correspond to extremely high densities of energy deposition and under these conditions, very spectacular effects are observed. The hammering effect of track-generating ions in amorphous materials and the damage of metallic systems were some of the most unexpected and remarkable effects of SHI irradiation. The development of criteria for phase stability under irradiation is one of the challenges for the next years. Cluster beams have largely contributed to the understanding of the track generation. Nowadays, the attention paid to the effects of SHI on organic materials is rising. The interest on biological effects and especially on heavy-ion radiotherapy partially explains this trend. The interest of the results obtained on model systems, as simple polymers or plasmid DNA, goes beyond this research area and are instructive for the life-science studies.

The radiation-induced material modification is also a tool for basic research in other branches of physics. The latent tracks induced by SHI are the defects that have found a marked interest for basic studies. Columnar defects induced by fast heavy ions are ideal pinning centres for flux lines in high-T_c-superconductors. Induced latent tracks in metallic compounds produce magnetic nanostructures and allow unique studies on nanomagnetism.

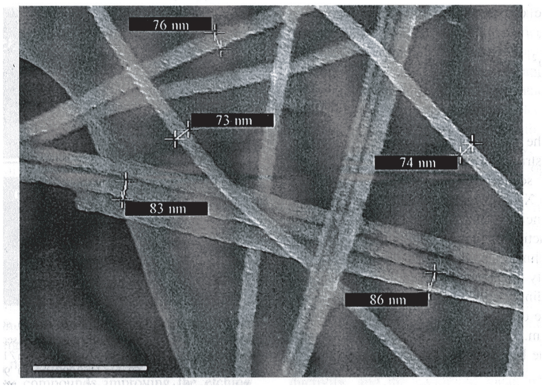


Figure 9.5: Electrodeposited nanowires observed with a scanning electron microscope after the dissolution of the polycarbonate track etch membrane template (E.Ferain *et al*). Some nanowire diameters are given. Scale bar is 500μm.

Nuclear techniques are also currently applied for material characterisation in industrial and fundamental research in Condensed Matter Physics. In this domain, technical developments, new methods and applications have opened interesting perspectives during the last years.

These developments concern in particular neutron-scattering studies of condensed matter, a standard technique that provides insight into the structural and magnetic behaviour of materials. Vast progress has been made on neutron detectors and spallation neutron sources, which drive new and powerful neutron facilities being projected over the world. Also, significant progress has also been achieved in what concerns methods using exotic beams, such as positron and μ-Spin Resonance Methods. Recent technical achievements, which allow small numbers of muons to be implanted at very low energy, are boosting a wealth of new applications where the material microscopic properties are studied near the surfaces at the nanometer scale. In what concerns techniques using standard ion beams, high depth and lateral resolutions have been reached for materials analysis and microfabrication. These improvements are related to the use of focused ion beams and of detectors with very high energy resolution. Atomic depth resolution may be reached near surfaces; laterally the precision for lithography and topography is of the order of 10-100 nm.

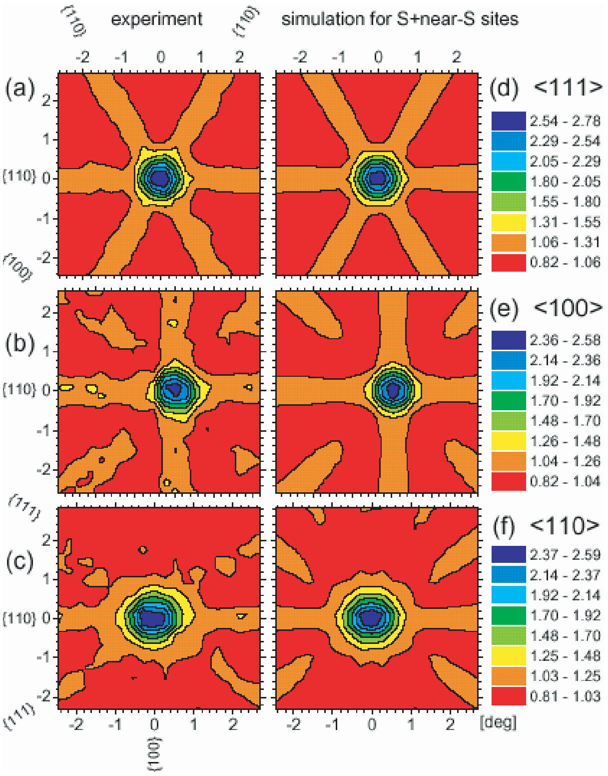


Figure 9.6: Blocking effects from implanted radioactive nuclei. (a), (b) and (c) Normalised emission yields of the integral β-intensity in the vicinity of $\langle 111 \rangle$, $\langle 100 \rangle$ and $\langle 110 \rangle$ directions of implanted ^{67}Cu into n$^+$-Si:As; (d), (e) and (f) are best fits of simulated patterns to the experimental yields (U.Wahl *et al*).

Finally, the use of radioactive ion beams gives access to sophisticated nuclear techniques for Solid State Research (Figure 9.6). The experiments are performed on-line at radioactive isotope separators. These facilities provide new atomic-scale tools, which are applied to study local fields, impurity lattice sites and identify the element responsible for macroscopic properties in the bulk, interfaces and surfaces of a large range of materials.

9.4 Concluding remarks

The potential of nuclear physics for interdisciplinary research and applications is quite large. Only a limited number of examples have been given here which illustrate the richness of the field. The applications of nuclear physics are also important as a vehicle to increase public appreciation of the achievements of our science. Nuclear physics makes indeed an essential contribution to the welfare of our society in many respects. Biomedical applications as well as environmental studies have a non-negligible impact on our society. Barriers between communities are progressively vanishing for their mutual benefit. In that context, the development of multi-disciplinary research teams should be strongly supported. This continuous interaction with other communities is essential as different fields may share concepts, models, and techniques. A good example is the cross-fertilisation between nuclear science and atomic and condensed matter physics. There are numerous spin-offs of nuclear technology. Good examples are accelerators, detectors, lasers, ion traps, and ECR ion sources. The forthcoming publication of the survey of the facilities, which provide access to application-oriented research, gives a very good illustration of the potential for applications using the powerful tools which are provided by these facilities. There is a need to increase the visibility of applied nuclear science in universities. In that respect, the role of small university facilities remains essential. Finally, it should be clear that one should not establish a hierarchy between basic and applied physics. However, it should also be clear that no high quality application studies would be achieved without a continuous high quality and creative basic research.