Opportunities to Extend Canadian Leadership in Nuclear Physics Research

Prepared by the Canadian Institute of Nuclear Physics for the
NSERC Subatomic Physics Long Range Planning Committee

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Chapter 1

Introduction

Through the aegis of the Canadian Institute of Nuclear Physics (CINP), the nuclear physics community has gathered together to outline its vision for the next 5 years and beyond. That vision is summarized in this brief, prepared by a representative committee consisting of the CINP Executive Director and the Chairs of the Five CINP Scientific Working Groups, "The CINP Brief Committee". Our duty was to gather community input and prepare a document placing the Canadian nuclear physics contributions within a long-term and international context, and make some overall recommendations. We hope that it will be of value to the NSERC Subatomic Physics Long Range Planning Committee as it works to establish the vision and goals for the whole subatomic physics community in Canada.

1.1 Consultation process

The consultation process we followed is outlined below. In 2014, following NSERC's announcement of the upcoming Long Range Plan, the CINP Board and Executive Director undertook a review and renewal of its Scientific Working Group (SWG) leadership. Two SWG Chairs agreed to five year renewals of their terms, while the leadership of three SWGs were changed. Of these three, two were selected via contested elections among the respective SWG memberships. The SWG Chairs, plus the Executive Director form the Brief Writing Committee, ensuring broad representation from all of the sub-disciplines of nuclear physics.

A two-day Town Hall meeting was held immediately prior to the 2015 CAP Congress in Edmonton, June 13-14. Participants were requested to submit a draft written document on their activities, plans and HQP training two weeks before the Town Hall meeting (May 29), and all were given an opportunity to revise their written briefs afterward, reflecting the discussions at the meeting. The Town Hall meeting itself was well attended, with presentations made by 24 groups. An additional three hours were reserved for discussions, which were lively. Groups not able to attend the meeting were also welcome to submit written briefs, and several did so. The committee also asked for briefs from two groups who were not previously active participants in the CINP: accelerator physics, and the EXO Collaboration.

Following this extensive community input, the committee members worked on their assigned sections in June and July, meeting several times by teleconference during this period to discuss issues and develop a cohesive plan. The committee then met in person at TRIUMF August 6-7 to finalize the brief. After some further edits, the draft brief was released to the Canadian nuclear physics community for comment on August 28. Responses were due September 10. A second draft incorporating these comments was released on September 18 with final comments due September 24. We are confident this final document reflects the consensus of the community.

1.2 The big questions in nuclear physics

The goal of nuclear physics research is to understand the origin, evolution and structure of visible matter in the universe. This is a far-reaching mission that requires a balanced program of experimental and theoretical efforts to address a number of key questions of significance to the larger scientific community. It is important to note that there is broad international consensus on these questions, as indicated by reports from the U.S. Nuclear Science Advisory Committee (NSAC) and the Nuclear Physics European Collaboration Committee (NuPECC). Here, we give a summary of these big questions and use them to place the Canadian nuclear physics effort in an international context.

1.2.1 How does the internal structure of the nucleons proceed from QCD?

For many years, we have known that nucleons are composite particles made up of quarks and gluons. We have partial answers from high-energy physics to questions such as how the quarks are distributed in the proton and how they move, and the 2004 Nobel Prize was awarded for the discovery of asymptotic freedom within the context of perturbative QCD. But QCD is still unsolved in the confinement regime, where the quark coupling strength is too large to allow perturbative methods to be used, and one of the central problems of modern physics remains the connection of the observed properties of the hadrons to the underlying theoretical framework provided by QCD. The solution of this problem requires advances in both theory and experiment. Recent advances in lattice QCD, in combination with chiral perturbation theory, make it possible to extrapolate full lattice QCD simulations to physical quark masses, and thus allow direct comparison to experimental observables. In addition, further developments in computational methods and decisive breakthroughs are anticipated in the near-future. Experiments designed to make detailed comparisons with QCD predictions are high-priority endeavours of research at facilities across the USA, Europe and Japan, with goals of obtaining: a tomographic view of the quarks and their motion within the nucleon; the elucidation of the role of gluons and gluon self-interactions in nucleons and nuclei; and a detailed understanding of how QCD governs the transitions of quarks and gluons into pions and nucleons.

Canadians have leadership roles in a number of experiments at offshore facilities, including detailed measurements of proton and pion structure, and investigations of the spectrum of hybrid mesons containing explicit gluonic degrees of freedom. These are all quantities that can be computed on the lattice, and so can be used to test our detailed understanding of QCD. From the beginning, Canadian theorists have been major contributors to lattice calculations, and to other areas of import to these measurements such as radiative corrections.

Fig. 1.1 provides an example of a recent Canadian contribution to an international research effort. Canadian investigators lead a program at the Mainz Microtron (Germany) which aim to measure the proton's spin polarizabilities for the first time. Spin polarizabilities describe the "stiffness" of the proton's spin against electromagnetic-induced deformations relative to the spin axis, defining the frequency of the proton's spin precession induced by variable electromagnetic

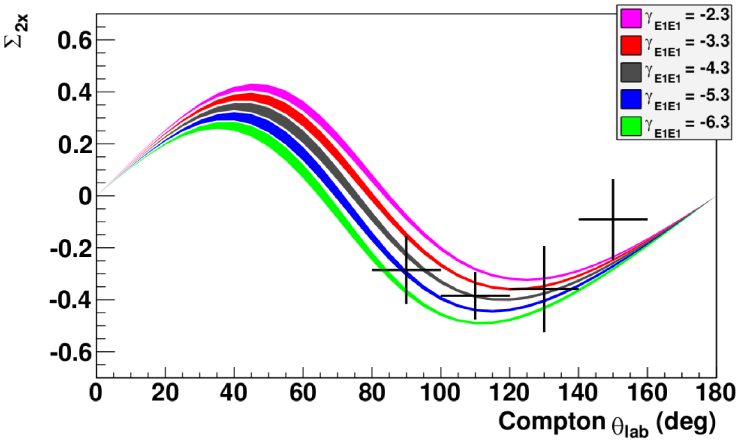

Figure 1.1: Σ_{2x} results for E_γ =273-303 MeV versus θ_{LAB} [Martel *et al.*, Phys. Rev. Lett. 114, 112501 (2015)]. Overlaid are calculations where the spin polarizability γ_{E1E1} is varied, as indicated, and constraints from other prior Compton scattering data are applied (allowed to vary within experimental errors).

fields. The effort involves the measurements of a series of single and double-spin asymmetries in Compton scattering, and an analysis of these asymmetries in a theoretical framework provides the linkage to the underlying spin polarizabilities. Fig. 1.1 shows the first-ever measurement of the Compton double-spin asymmetry Σ_{2x}, utilizing a circularly-polarized photon beam incident upon a transversely-polarized proton target. The data are consistent with the value $\gamma_{E1E1} = 3.5 \pm 1.2$ fm^4, providing the first experimental measure of this quantity.

1.2.2 What are the phases of strongly interacting matter, and what roles do they play in the cosmos?

Nuclei make up 99.9% of the visible matter in the universe. 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 color-superconducting. Exotic nuclear matter can also be created by colliding nuclei at relativistic energies. In this case, 'nuclear temperatures' can reach values that represent a state of matter (the quark-gluon plasma) as it existed during the first moments after the Big Bang. This is an active field of study at international facilities such as RHIC in the USA, and the LHC at CERN. There are a number of very active Canadian theorists who are making significant contributions to our understanding of the phase diagram of nuclear matter. Their work has significant bearing on the quest to characterize the properties of the quark-gluon plasma, and for our understanding of astrophysical phenomena such as neutron star structure and the evolution of the early universe.

In recent years, the nuclear theory group at McGill University has developed and put forward a 3D, relativistic, viscous fluid-dynamical approach that has been successfully used to model the time-evolution of the high-energy nuclear collisions. This enabled an extraction of the shear viscosity to entropy density ratio (η/s): a fundamental property of QCD. This approach has recently been used by researchers of the McGill group, with collaborators, to show how measuring the photon spectrum could be used as a thermometer [Phys. Rev. C 89, 044910 (2014)] and a viscometer [Phys. Rev. C 91, 024908 (2015), *Editor's Choice*] of the quark-gluon plasma. Figure 1.2 shows

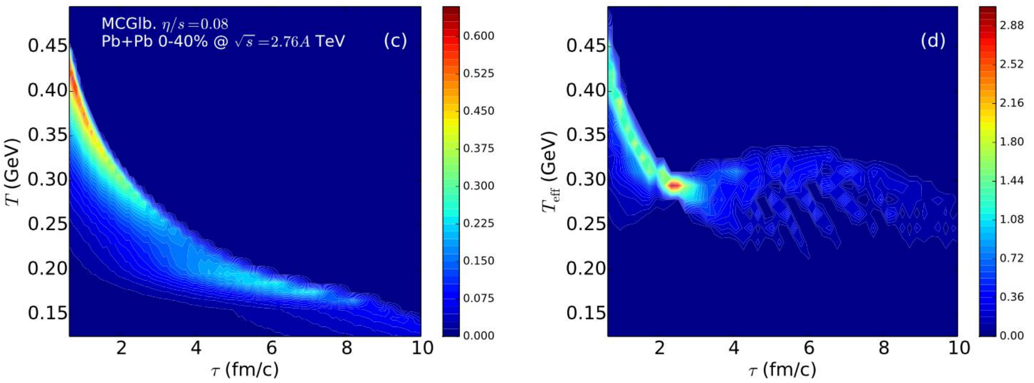

Figure 1.2: The left panel shows the real temperature distribution of hydrodynamics fluid cells, as a function of their proper time. The right panel shows the effect of the Doppler shift contamination on the temperature extraction. The fluid dynamics simulation was done for Pb + Pb collisions at LHC energies (2.76 TeV/nucleon), in the 0-40% centrality class. The colours refer to the net photon spectrum. The value of the shear viscosity used in the calculation is $\eta/s = 1/4\pi$. This figure is from [Phys. Rev. C 89, 044910 (2014)].

the important effect of hydrodynamic expansion on the extraction of the effective temperature of the quark-gluon plasma.

1.2.3 What is the nature of the nuclear force that binds nucleons into stable nuclei and rare isotopes?

A central goal of nuclear physics is to explain the properties of nuclei and nuclear matter. This is a formidable task which is best approached in steps: from the basic equations of QCD, through effective field theories; to inter-nucleon interactions and few-body systems; and further on to the many approaches used to describe nuclear structure, ranging from exact methods such as Green's Function Monte Carlo (GFMC) to the shell model and density functional theory. While calculations based on the nucleon-nucleon interaction have achieved quantitative success in reproducing the features of light nuclei, detailed agreement is still lacking for heavier nuclei. This is a problem that is common to the description of other complex systems, such as proteins. In nuclear physics, the development of a comprehensive, predictive theory of complex nuclei remains a key goal. Worldwide, this has driven the recent development of high-quality radioactive beams, as they allow us to move from a one-dimensional picture where the mass of a nucleus varies, to a two-dimensional picture where both proton and neutron mass numbers vary over a wide range. With the recent completion of much needed detector infrastructure at TRIUMF's ISAC facility, and the securing of funds needed to complete the ARIEL electron LINAC, Canadians have a unique opportunity to make substantive advances in the field. Further work involves off-shore facilities such as the Canadian Penning Trap at Argonne, and significant contributions to experiments at the GSI Helmholtz Center for Heavy Ion Research in Germany and Jefferson Lab. Observations to date indicate striking anomalous behaviour in these rare isotopes, and the study of nuclei having high neutron or proton imbalances will provide the missing links to our present understanding. Recent theoretical advances show strong promise to form a better linkage between the fundamental theory of strong interactions, and the quantitative description of nuclear many-body phenomena. This includes not only the new and exotic properties we observe and expect in radioactive nuclei, but also neutron stars.

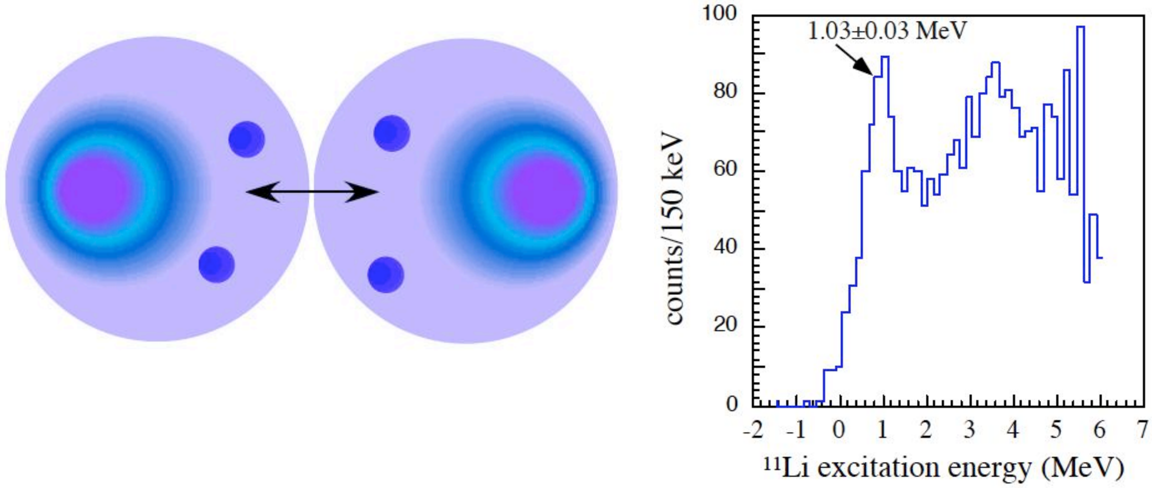

Figure 1.3: First experimental observation of the soft-dipole resonance in the halo nuclei, ^{11}Li. Left: Schematic view of halo and core oscillation giving rise to soft dipole resonance. Right: The soft dipole resonance peak observed in ^{11}Li.

A recent Canadian achievement in this area is the study of the ^{11}Lithium neutron halo. It has such an extended spatial distribution that ^{11}Li has a size similar to ^{208}Pb. The IRIS program at TRIUMF-ISAC investigated this halo through the inelastic scattering using two different probes, namely protons and deuterons. The first result [R. Kanungo *et al.* Phys. Rev. Lett. 114, 192502 (2015)] from deuteron inelastic scattering shows clear evidence of the soft-dipole resonance at a very low excitation energy of 1.03(03) MeV (See Fig. 1.3), and furthermore elucidates for the first time that this resonance has isoscalar character. This challenging experimental result was made possible by two world-unique features: the world's highest intensity of ^{11}Li radioactive beam available from TRIUMF-ISAC and the solid hydrogen/deuterium reaction targets of the IRIS facility.

1.2.4 What is the role of nuclei in shaping the evolution of the universe?

Primordial nucleosynthesis that occurred during the cooling following the Big Bang, gave rise to primordial abundances of the lightest elements H, He, and Li. Nearly all other chemical elements in the universe are produced as a result of nuclear reactions in stars, and are expelled into the interstellar medium by supernova and nova explosions, neutron-star mergers, etc. It is a central goal in physics to explain the origin of matter in the universe, and nuclear astrophysics addresses the many fundamental questions involving nuclear physics issues that remain open. These include: the origin of the elements; the connection between the observed solar abundances and nuclear structure phenomena; the mechanism of core-collapse supernovae; the structure and cooling of neutron stars, and the equation of state for asymmetric nuclear matter. Nuclear astrophysics has benefited enormously from progress in astronomical observation and astronomical modeling, and a new era in nuclear astrophysics has opened with the use of radioactive-beam facilities dedicated to the measurement of short-lived nuclides of relevance to astrophysics. These include direct and indirect measurements of the various reaction rates and the determination of masses, half-lives, and the structure of exotic nuclei. Canadians working at the ISAC facility at TRIUMF play a key role in this active field, complementing experiments underway in the USA, Europe and Japan. Nuclear astrophysics involves much inter-disciplinary work between nuclear physicists, stellar modelers, and astronomers – as can be seen in Sec. 3.3.1.1 by the various national and international projects and research centers in which Canadian astrophysicists participate.

A recent highlight from the DRAGON facility at TRIUMF is the first direct measurement of $^{18}F(p,\gamma)^{19}Ne$ [C. Akers et al., Phys. Rev. Lett. 110 262502 (2013)] within the astrophysically relevant Gamow window. This reaction is one of the important reactions which destroy ^{18}F, the largest source of 511 keV γ-rays in novae. Sensitivity studies revealed that a change of a factor 10 in the $^{18}F(p,\gamma)$ rate changes the ^{18}F abundance by a factor 3. The deduced resonance strength at E_R= 665 keV was found to be a factor 14 lower than previously assumed, which led to the conclusion that this resonance has no significant contribution to the total reaction rate at nova temperatures. This finding strengthens the importance of the resonance at E_R= 330 keV, which is presently not accessible for direct measurements. However, indirect measurements at DRAGON via the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction are planned and are presently the only conceivable way to get some experimental information about this low-lying resonance.

In addition, the TUDA setup, which is also located at TRIUMF, has enabled the extension of the $^{18}F(p,\alpha)^{15}O$ reaction into the astrophysically-important energy regime. This reaction is one of the most important reactions for novae since it dominates the destruction of ^{18}F [C. Beer et al., Phys. Rev. C83, 042801(R) (2011)].

1.2.5 What physics lies beyond the Standard Model?

The forces and symmetries that were in play in the early universe have shaped the cosmos as we know it today. Nuclear physicists have long studied the fundamental symmetries of the weak interaction, and probed the Standard Model with very precise, low and intermediate-energy experiments. While the Standard Model has proved to be remarkably resilient to these tests, there are a few indications of potential shortcomings in the model. If the breakdown is confirmed, we could be seeing the first indications of new physics beyond the Standard Model. A new generation of experiments, designed to push the limits of discovery and precision, can be grouped in terms of the mysteries they hope to shed light on.

1. Why does the universe have an imbalance of matter over antimatter?

   The Standard Model is unable to explain how this excess has arisen. An essential ingredient in the possible resolution of this enigma is the presence of new interactions that do not look the same when the direction of time is reversed. Nuclear physicists are seeking to uncover time-asymmetric forces with precision measurements of the properties of the neutron, atoms, and mesons. At TRIUMF, a new ultra-cold neutron facility is under development, with a search for a permanent electric dipole moment of the neutron as the first experiment. In addition, Canadian researchers plan similar searches in atomic systems at ISAC. Finally, the ALPHA experiment at CERN will continue to test our understanding of antimatter by directly comparing the atomic spectra, and the gravitational acceleration of hydrogen and antihydrogen.

2. What is the nature of the "super-weak" forces that disappeared from view when the universe cooled?

The Standard Model is one of the best-tested theories in physics, but it is believed to be incomplete. Both nuclear and particle physicists are continually searching for indications of additional, undiscovered forces that were present in the initial moments after the big bang. Particle physicists probe the TeV mass range directly at the LHC, but high-precision experiments at lower energy probe mass scales and parameter spaces not accessible at the high-energy accelerator facilities. Any deviation from the Standard Model discovered at LHC must be reflected in a corresponding rare interaction at lower energy. Parity violation studies in atomic systems at ISAC and in electron scattering at JLab will test our detailed understanding of the electroweak interaction, in a way which is sensitive to new physics in the multi-TeV mass range. Dark matter searches at SNOLab will also help clarify the nature of these interactions.

3. What is the nature of the observed neutrino oscillations?

   The resolution of the solar and atmospheric neutrino puzzles by SNO and Super-Kamiokande opens up possibilities for exciting discoveries in the neutrino sector. The observation of the extremely rare neutrinoless double-beta decay process at SNOLab would revolutionize our understanding of lepton number in the Standard Model and would provide a determination of the mass scale of the neutrino, if the nuclear matrix element can be determined precisely from theory.

There are many recent achievements by Canadian groups addressing these issues. The ALPHA (Antihydrogen Laser Physics Apparatus) at CERN aims to test the fundamental symmetries between matter and antimatter using trapped antihydrogen atoms. ALPHA-Canada is the largest group in ALPHA, and is responsible for almost all of the subatomic aspects of the experiment. ALPHA's first demonstration of antihydrogen trapping in 2010 [Nature 2010] generated world-wide interest among the scientific community and beyond. Since then, they have further demonstrated (1) confinement of antihydrogen for 1000 seconds [Nature Physics 2011], (2) spectroscopic measurements of antihydrogen via microwave-driven hyperfine transitions [Nature 2012], (3) a technique to measure the gravitational mass of antihydrogen [Nature Comm. 2013], and (4) the charge neutrality of antihydrogen [Nature Comm. 2014]. The ALPHA-Canada team members and students have been recognized with various prestigious awards, including the 2013 NSERC John C. Polanyi Award for outstanding advances in science and engineering, the 2011 John Dawson Award for the trapping of antihydrogen, and the CAP-DNP Thesis Award for the detection of trapped antihydrogen.

A second example is the Qweak experiment at Jefferson Lab, which has significant Canadian leadership and instrumentation. It is the first high precision measurement of the protons weak charge, via parity-violating electron-proton scattering (PVES). Early results, based on the Qweak commissioning run (4% of the total data), were published in 2013 [Androic et al., Phys. Rev. Lett. 111, 141803 (2013)] and attracted considerable attention. The preliminary result $Q_W^p(PVES) = 0.064 \pm 0.012$ is in good agreement with the Standard Model prediction $Q_W^p(SM) = 0.0710 \pm 0.0007$. A detailed analysis of the full Qweak data set is nearing completion, with final results expected to be released by 2016. They will place significant constraints upon hypothesized multi-TeV mass contributors to PVES.

The Canadian Penning Trap Collaboration at Argonne National Lab have also seen recent success with their beta-neutrino correlation measurement with trapped ^{8}Li ions [G. Li *et al.*, Phys. Rev. Lett. 110, 092502 (2013)]. Here, the decay $^8\text{Li} \rightarrow ^8\text{Be}^* + \beta^- + \bar{\nu} \rightarrow \alpha + \alpha + \beta^- + \bar{\nu}$ is measured. Due to the relatively large recoil energy, the α's from ^{8}Be break-up are easy to detect. The Standard Model predicts the Gamow-Teller decay to be purely axial vector, and the greatest sensitivity of the measurement to possible tensor interactions is when the α's and β 's are coaxial. The published result from the 2011 run is consistent with Standard Model expectations, placing significant constraints on Tensor interactions. A higher statistics run was successfully completed in 2014 and a new result with significantly reduced error bars is anticipated in the near future.

In the sections following the Executive Summary, we will discuss the contributions of Canadians to these questions in greater detail, placing this work in the broader context of the field as a whole, and giving an indication of where this work is expected to lead in the next 5 years and beyond.

1.3 How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Canadian nuclear physicists are at the forefront of their fields - studies by the Council of Canadian Academies and Science Metrix both found that Canada is a "world-leader" in subatomic physics and astrophysics. [1] Nuclear technology has an impact in a variety of scientific fields; only computers, microelectronics and possibly laser technology surpass nuclear physics techniques as the most widely used set of tools in science. For example, nuclear techniques are the gold standard for measuring the age of ancient objects, from the archaeological to the cosmic time scales. Nuclear-tracer techniques are used to unravel bio-chemical pathways, to determine the efficiency of chemical reaction vessels, and to measure the flow of ground water. Another example is that of the GlueX experiment, at JLab. That collaboration's requirement for stringent silicon photomultiplier (SiPM) specifications has produced tile arrays that are now used in medical imaging. Most, if not all, of these technologies were not developed for the specific application for which they are used, but came about as a result of the pursuit of fundamental nuclear physics research.

An example of the importance of having a large base of knowledgeable and skilled researchers is evident in the recent success of an interdisciplinary team of researchers including Canadian nuclear physicists. This team set out five years ago to develop a reliable, alternative means of producing a key medical isotope, $^{99}\mathrm{Tc}^{m}$. The project resulted in over a dozen scientific publications, several provisional patents, and a training opportunity for more than 175 individuals. The team demonstrated true collaboration in solving this worldwide healthcare challenge and received the NSERC Brockhouse Canada Prize for Interdisciplinary Research in Science and Engineering for this groundbreaking, and life-saving, technique. [2] This achievement is a direct result of investment provided by the Government of Canada through programs at the Natural Sciences and Engineering Research Council, the Canadian Institutes of Health Research, and Natural Resources Canada.

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[1] "The State of Science and Technology in Canada, 2012." The Expert Panel on the State of Science and Technology in Canada, Council of Canadian Academies; http://www.scienceadvice.ca/en/assessments/completed/science-tech.aspx

[2] http://www.triumf.ca/sites/default/files/NR-Feb-17-2015-Brockhouse-vF.pdf

Chapter 2

Executive Summary of Recommendations

The Canadian nuclear physics community is pursuing a diverse set of research endeavors which address key questions identified by broad international consensus as being of major importance in understanding the origin, evolution and structure of visible matter in the universe. These endeavors are carried out both at TRIUMF in Canada, and at international facilities where researchers lead exciting, unique opportunities not available onshore. In the 2016 to 2026 time period, the Canadian nuclear physics community is primed to leverage scientific discoveries from the investments which have already been made into research equipment and infrastructure both at TRIUMF and abroad. Our specific recommendations for maximizing Canadian scientific output in nuclear physics research are detailed in Chapter 6 and are summarized here for convenience.

1. Enhance nuclear theory support.

   Some of the world leaders in nuclear theory, in fields such as ab-initio nuclear structure and relativistic heavy ion collisions are based in Canada. These include new nuclear theory hires since the last long range plan, as well as established researchers. A great opportunity exists to further strengthen and grow this program, with strategic investment in HQP who can accelerate the efforts of these recognized world leaders at the fore-front of an exciting and fast-moving discipline that is intimately linked to Canadian experimental efforts in nuclear physics.

2. Make strategic investments in additional HQP to capitalize on new or recently-upgraded facilities.

   The last five years have seen large strategic investments in our field and the development of several major new experimental facilities. The experimental studies enabled by these new facilities have very high scientific merit and Canadians yearn to take advantage of these opportunities.

   - A central component of TRIUMF's current 5-year plan is the full scientific exploitation of the ISAC and ARIEL facilities at TRIUMF, and the timely completion of ARIEL-II. This has played a major role in the $45M increase to the TRIUMF NRC budget that will benefit the entire subatomic physics community. This will lead to a very substantial increase in beam time available at the ISAC facility within this planning period, and allow a large number of high priority measurements to more quickly move ahead.

   - In the USA, the Jefferson Lab 12 GeV upgrade is now complete, leading to abundant scientific opportunities in experiments that Canadians lead in Halls D, C, and A.
   - At CERN, the ALPHA-Canada Collaboration will be embarking on a large expansion of their scientific program as a result of the positive CFI decision on ALPHA-g.
   - The TRIUMF Ultra Cold Neutron (UCN) source has been quickly ramping up its activity, with commissioning planned for 2017.

   Significant additional graduate students and postdocs are needed to capitalize upon these investments, and ensure continuing Canadian leadership in these fields.

3. Maintain a diverse program of excellence in experimental and theoretical nuclear physics research.

   The Canadian nuclear physics program is grouped around several key questions that are each internationally recognized as being of high priority. Recognizing the need to maintain scientific excellence and a critical mass of effort, the Canadian nuclear physics research community has self-selected where to to concentrate its effort, taking leadership roles or making significant contributions in initiatives addressing these questions both onshore and offshore. However, there are many inter-connections between these questions, and advances in one area often depend on progress in a complementary area. Therefore, a diverse nuclear physics program addressing these key questions must be maintained in all funding scenarios.

4. Provide capital funding for future high impact experiments.

   Several major experimental initiatives under development promise a substantial improvement over current knowledge, and will require significant capital funding if these gains are to be realized. Large projects that are on the planning horizon include:

   - The MOLLER experiment at Jefferson Lab, followed at a later date by SoLID.
   - nEXO at SNOLab, if it is selected by the DOE as their next-generation neutrino-less double-beta decay experiment.
   - The Phase 2 upgrade of the Ultra-Cold Neutron facility at TRIUMF.
   - Further detector enhancements at ISAC are also in early planning stages, or opportunities may arise at the next-generation in-flight facilities FRIB in the USA or FAIR in Germany which are both presently under construction and expected to provide first beams for nuclear physics experiments within the next 5-7 years.

5. Provide funds for next-generation detector and accelerator R&D.

   There are several longer-term opportunities for Canadian nuclear physicists.

   - Internationally, there has been much activity towards the construction of an Electron-Ion Collider (EIC) in the USA in the coming decade. The scientific case for this facility has received very favorable reviews, and Canadian nuclear physicists are taking roles in the planning and prototyping for this new facility.

- Next-generation extensions to the ISAC facility are just beginning to be discussed. One of several possibilities is to construct an ion storage ring fed by further accelerated beams from ISAC-II, which would enable experiments to be performed with very neutron-rich light nuclei, beyond the reach of future in-flight facilities like FRIB.

Opportunities such as these require ongoing investments in detector and accelerator R&D to assure the continued excellence of Canadian nuclear physics research in coming decades, and to continue the positive impacts that fundamental research has had on Canadian society and industry.

Chapter 3

Physics Case

In the following chapter several projects and setups with Canadian involvement and their physics cases are described. The chosen format to show the involvement of Canadian universities and research centers and international partners is "**Project** (Location) alphabetical order of Canadian partners; involved international countries". It should be noted that due to the strong involvement of the local groups in a project, e.g. for setups at TRIUMF, the facility is not repeated in the list of Canadian universities and research centers, e.g."**Detector X** (TRIUMF) Guelph, SFU, UBC; UK, USA".

3.1 Hadron structure and QCD

3.1.1 Overview

The theory of the nuclear strong interaction is quantum chromodynamics, or in short, QCD. It controls the short distance interaction of nucleons – the constituents of the atomic nucleus – and it also controls the interactions of the constituents of the nucleons: quarks and gluons. Of all of the fundamental interactions known to us, it is the strongest and also the most mathematically intricate. One of the most fascinating aspects of QCD owes to its intrinsic non-linearity: unlike the photons in Quantum Electrodynamics (QED), the gluons carry a "colour electric charge" and can therefore interact with themselves. This unusual feature stands behind what has become known as the running of the QCD coupling constant: α_s, the strong-interaction equivalent of the electromagnetic fine structure constant becomes smaller as the energy scale with which it is probed grows in magnitude. This behaviour is opposite to what is known to happen with other fundamental interactions. At high energies, the weakening of α_s leads to *asymptotic freedom*. This fact, or rather its theoretical elucidation by Gross, Politzer, and Wilczek was awarded the Nobel Prize in Physics in 2004, and has been unequivocally confirmed by experimental measurements, as shown in Figure 3.1. Asymptotic freedom is accompanied by *infrared slavery*: at larger and larger distances the coupling grows, rendering calculations that rely on perturbation theory unreliable. As the strong force grows larger with increasing distance, so does the gluon population and the quark-antiquark pair production. In fact, the colour force becomes so strong that the quarks and gluons (collectively known as *partons*) are not able to escape. This is the phenomenon of *confinement* that is currently not derivable from first principles, but does receive empirical support from all we know of QCD.

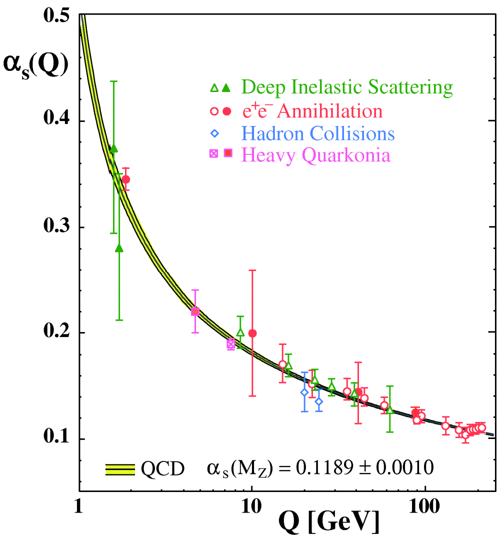


Figure 3.1: The QCD coupling, α_s as a function of energy scale, as extracted from a variety of different experiments. The curves are theoretical predictions of QCD. This figure is from S. Bethke, Prog. Part. Nucl. Phys. 58, 351 (2007).

As the mass scale of the proton and neutron lies in the nonperturbative regime of QCD, theoretical guidance there exists in two forms. The first is lattice QCD: the equations of quantum chromodynamics are discretized on a four-dimensional spacetime lattice, and solved numerically with the coupling strength appropriate for hadronic physics. This procedure is performed at considerable cost in computer time and memory, and progress can typically only occur within the realm of large collaborations using high-performance computing (HPC) facilities. The other approach is that of effective theories: models are devised with the degrees of freedom appropriate for the problem at hand, and with the symmetries that are germane to the underlying fundamental theory, QCD. This is the modern understanding of the success of nuclear models that has been successfully applied over the last eighty years. Model building is an essential part of the discovery process, as these often pave the way to the elaboration of more universal theories. How to understand the transition from the degrees of freedom of QCD to those of nuclear and hadronic physics currently constitutes major theoretical and experimental challenges, and this quest lies at the very core of the mainstream research efforts in contemporary nuclear physics. This area is actually a perfect example of a fruitful collaboration between the theoretical and experimental communities. Canadians are involved in both; the experimental aspects are discussed next, while the research in theory will be covered later in this document.

3.1.2 The Canadian program

3.1.2.1 The Thomas Jefferson National Accelerator Facility

The bulk of the Canadian involvement in experiments on hadronic physics and QCD is currently carried out at Jefferson Lab (JLab), a facility funded by the US Department of Energy's Office of Science. This facility's mission is to study how the degrees of freedom of QCD, quarks and gluons, assemble and interact to form nucleons and nuclei. It does so by performing scattering experiments of electrons on a variety of targets. This laboratory has just completed a major upgrade, and has doubled the energy of its electron beam to 12 GeV, see Figure 3.2. The upgrade offers 100% duty factor and high-intensity electron and tagged photon beams, with polarization possibility. The experiments performed at JLab by Canadians are GlueX, ones studying Deep Exclusive Meson Production, and ones looking at the structure of the nucleon as probed by a high-Q^2 probe.

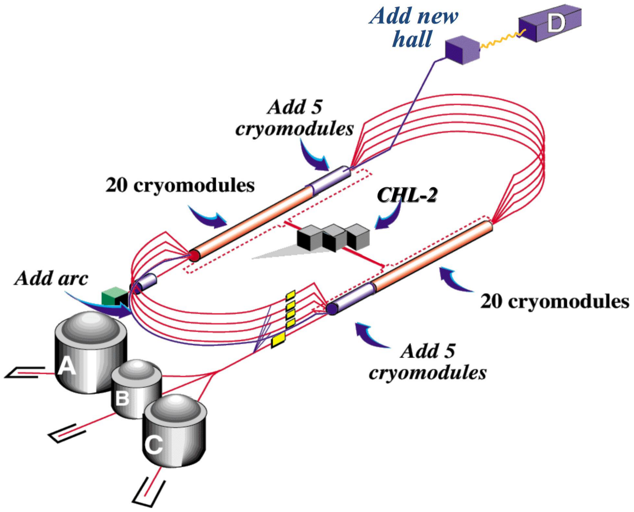


Figure 3.2: The Jefferson Laboratory upgrade involves doubling the maximum beam energy to 12 GeV, adding a new experimental hall, Hall D, and upgraded capacities (beamlines, detectors) in Halls A, B, and C.

GlueX (JLab) Regina; Armenia, Chile, Greece, Russia, UK, USA

The primary physics objective of GlueX is the production and classification of exotic and non-exotic hybrid mesons through their photo-production. Hybrid mesons may carry a valence gluon contribution. The physics of confinement is still not well understood and even though much progress has been made by lattice QCD, masses, quantum numbers and production cross sections of hybrid mesons are still an open question. Decay channels of such hybrids are also not certain. GlueX, in the new experimental JLab Hall D, will initially probe u and d quark systems. Eventually, with a detector upgrade (a direct internal reflection Cherenkov, DIRC)), hybrid meson nonets with s or $\bar{s}$ content will also be explored.

The validity of QCD may be explored by searching for so-called exotic states that have forbidden J^{PC} quantum numbers; these will not mix with any other $\bar{q}q$ states and can be thus identified experimentally without ambiguity. Indeed, recent lattice QCD calculations do predict that gluons can do more than bind quarks and antiquarks: they can manifest themselves as valence partons in mesons with integer spin values and quantum numbers that are impossible in ordinary two-body quantum systems. An example of such predicted mass spectra is shown in Figure 3.3.

The photon is expected to be particularly effective in producing gluonic excitations with exotic J^{PC}, as it has the same quantum numbers as a vector meson: $q\bar{q}$ with the two partons having aligned spins. The vector property of the photon offers another advantage in the identification of the reaction mechanism, which is greatly aided by employing linearly polarized photons. With the photon beam intensities in Hall D, GlueX will accommodate more photo-production data in a few

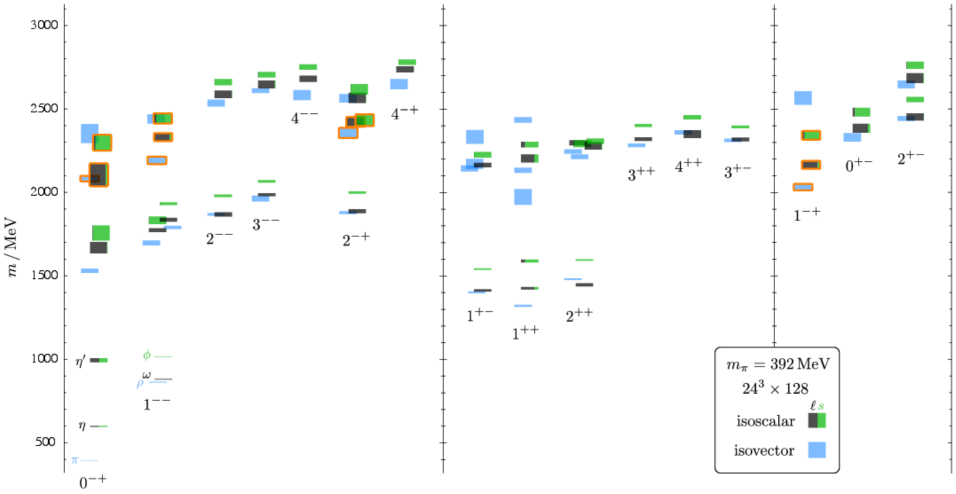


Figure 3.3: Lattice QCD results for isoscalar (green and black) and isovector (blue) meson mass spectrum. The statistical uncertainty in each mass determination is proportional to the vertical size of the relevant box. Boxes with an orange outline are the lowest-lying hybrid states; the three columns to the right are examples of exotic quantum numbers. This figure is from [Hadron Spectrum Collaboration (Dudek et al.), Phys. Rev. D 88, 094505 (2013)].

months than all the currently existing data on the subject. Canadians have been involved in the GlueX project since 2000, covering all phases of the project: initial physics formulation, conceptual design report and simulations, R&D and detector construction, Collaboration management (roles of Collaboration Board Chair, Deputy Spokesperson, Calorimetry Coordinator), and U.S. Department of Energy (DOE)-mandated project reviews.

Canadians assumed the responsibility for the R&D, the design and construction of the Electromagnetic Barrel Calorimeter (BCAL) and the R&D for its photo sensors. The construction of the BCAL was successfully completed in 2012, and it was the first detector ready for the 12 GeV Upgrade. The Canadian contributions continued towards the installation of the detector in the GlueX superconducting solenoid, and in turn-on efforts using an LED pulser system and cosmic rays. In parallel with the construction, extensive testing and quality control of the scintillating fibers for the BCAL and the preproduction SiPM units were completed, together with the associated simulations, to assure they all met rigid specifications.

The photo sensor R&D led to an impactful new development in large active area solid-state photo sensors, commonly referred to as silicon photomultipliers (SiPMs). In fact, the industry "standard" large-array format of SiPMs – now commercially available – was originally dictated by the BCAL requirements, that were defined by extensive simulations and studies carried out in close partnership with a European photonics company (SenSL). The new photo-sensor technology of large array SiPMs has opened up a new application of such sensors to medical imaging, among other applications in security and industry.

Within 2014, all the GlueX detector systems had been installed in Hall D and two commissioning phases with a photon beam were completed in the fall of 2014 and spring of 2015, respectively. All indications to date are that the detector systems operate as designed and, more specifically, the BCAL has met or exceeded specifications on performance. Specifically, clear definition of multi-track events in the GlueX detector were established within a few days of running, including cluster

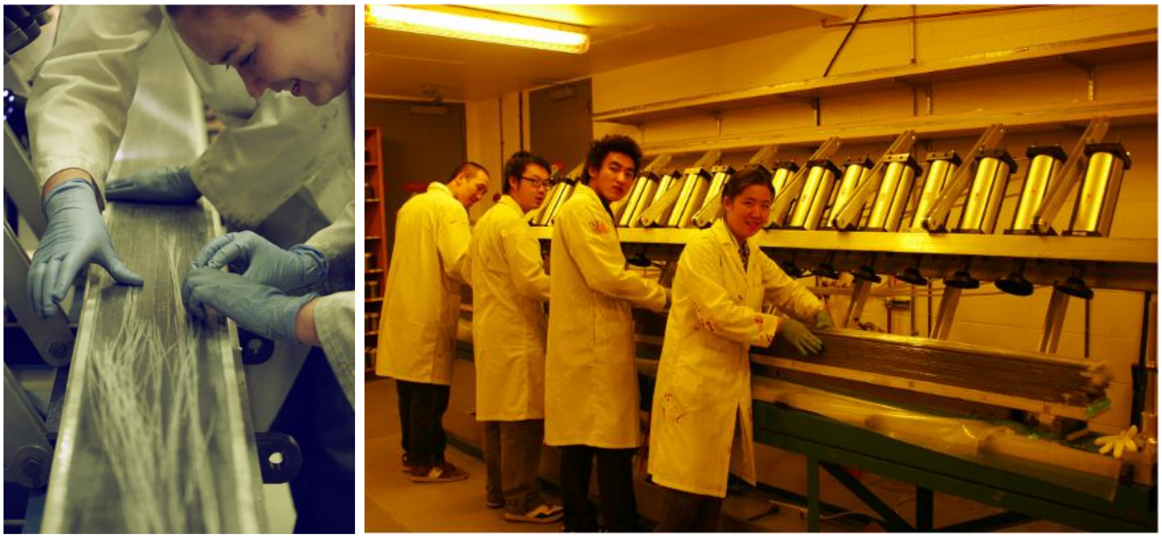


Figure 3.4: GlueX Barrel Calorimeter (BCAL) module construction by students at U. Regina.

hits in the BCAL detector that allowed the reconstruction of the π^0 mass with a width of about $\sim$ 7 MeV, which meets the design goal. This was made possible by precise comparisons between simulations and cosmic ray data, which allowed a remarkably accurate definition of the energy calibration constants and thresholds. It should be noted that in just a few hours of beam in April, a clear coherent bremsstrahlung peak with high degree of linear polarization off the newly installed diamond radiator was achieved, resulting in clean, polarized ρ^0 production. Physics running will formally start in 2016.

The Canadian involvement in experiments in JLab's Hall A aim at elucidating details of the structure of light nuclei and the nucleon at low to intermediate values of the four-momentum transfer squared (Q^2). The group is now poised to make continuing contributions out to very high Q^2. In the last several years of lead-up to Jefferson Lab's energy upgrade, two low-Q^2 experiments have been conducted with results just now being finalized for publication.

E08-010 (JLab) Saint Mary's; Greece, Slovenia, Spain, USA

This experiment ran in 2011, and was designed to probe "non-spherical" (quadrupole) contributions to the $N \to \Delta(1232)$ transition down to the lowest-ever-measured values of Q^2, hoping for a clearer connection to predictions which are now forthcoming from lattice QCD calculations. The ongoing analyses will be providing this new quadrupole component transition amplitude very soon.

E08-007 (JLab) Regina, Saint Mary's; France, Israel, Korea, Slovenia, UK, USA

Canadians contributed to the lowest Q^2 portion of this experiment designed to extract high precision measurements of the proton's electric-to-magnetic form-factor ratio ($\mu_p G_E/G_M$) at the lowest-ever values of Q^2 (down to 0.01 GeV^2). The first portion of E08-007 (which ran in the years prior) utilized recoil-proton polarimetry, and provided high-precision data down to Q^2=0.3 GeV^2, with the analysis re-confirming a proton radius consistent with other precision electron-based measurements (0.875 ± 0.010 fm), but inconsistent with precision muon-based measurements, 0.84087(39) fm. This inconsistency remains un-understood, but completion of the analysis of this very-low Q^2 portion (wherein the polarized-target technique was used) can clarify the accuracy of the electron-based radius extraction. The analysis is ongoing and results will appear soon.

In addition to the search for exotic quantum states, the tomography of nucleons and of nuclei now benefits from a powerful new tool: Deep exclusive meson production. Those challenging measurements, made by experiments installed in JLab's Hall C, do not benefit from a broad kinematical coverage, and thus proceed with a smaller rate than their inclusive counterpart. However, they can be used to access Generalized Parton Distributions (GPDs), via recently proven factorization theorems. The GPDs carry information on the distribution of partons in the transverse plane, in addition to the longitudinal information traditionally contained in the Parton Distribution Functions (PDFs).

E93-021/E01-004 (JLab) Regina; Armenia, Netherlands, USA

On larger distance scales, information about the spatial extent of hadrons is provided by measuring their elastic and transition form factors. The form factors of light mesons, especially the pion, are of interest. Indeed, the pion has a special role. It is the force carrier for the long-distance part of the strong interaction, the Goldstone boson of the spontaneously broken chiral symmetry, and also the lightest bound state of a $q\bar{q}$ pair. The previous Canadian involvement in JLab experiments E93-021 and E01-004 on measuring the charged pion form factor constitutes a strong foundation on which future efforts in this direction are building. The final results of these collaborations were published in 2014 and 2015, and some of these are shown in Figure 3.5. This effort has revealed clear evidence of the transition between hadronic and partonic degrees of freedom.

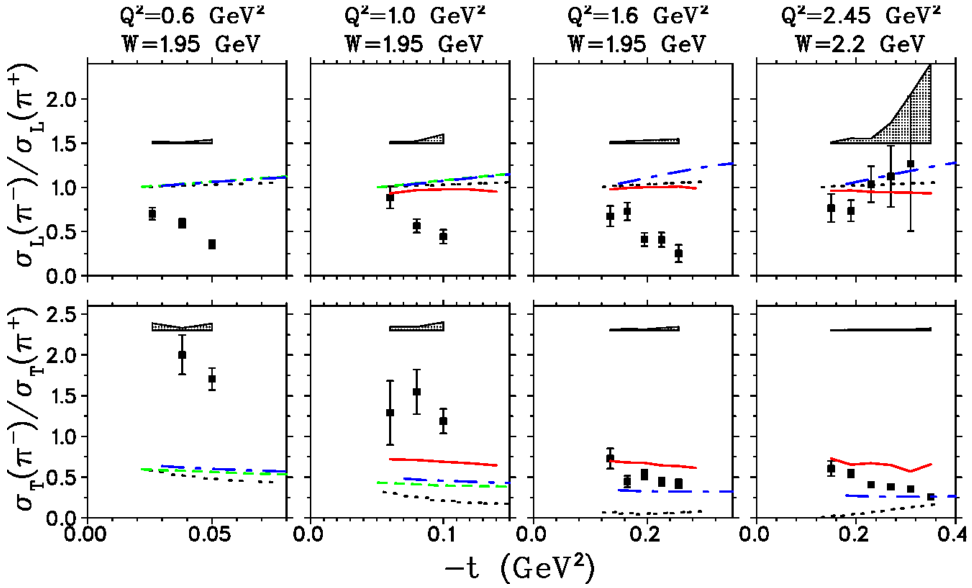


Figure 3.5: Shown here are results from the JLab F_π Collaboration, which studied exclusive $\pi^\pm$ electroproduction on the nucleon. The x-axis is the Mandelstam variable $-t = -(p_{target} - p_{recoil})^2$. A change in the ratio $R_T = \sigma_T^{\pi^-}/\sigma_T^{\pi^+}$ from unity at small $-t$ to $\sim 1/4$ at large $-t$ suggests a transition from hadronic to partonic degrees of freedom. The curves show the results of various theoretical calculations. This figure is from [G. Huber et al., PRL 112, 182501 (2014)].

3.1.2.2 Mainz Microtron

A2 Collaboration (MAMI) Mount Allison, Regina, Saint Mary's; Croatia, Germany, Italy, Russia, Switzerland, UK, USA

As already mentioned above, a portion of the Canadian experimental research program on QCD is carried out at facilities other than than JLab. One of those is MAMI, the Mainz Microtron (Mainz, Germany), where Canadians are members of the A2 Collaboration. The Mainz laboratory provides a high-quality, high-flux continuous-wave 1.5 GeV electron beam providing a beam of polarized photons, a refurbished near-4π CB-TAPS detector system, and a frozen-spin polarized proton target. These have allowed unique access to high-precision measurements of nucleon structure. Obtaining these new, precise nucleon-structure data is the aim of each of the experiments that have significant Canadian contributions.

Proton spin polarizabilities The first task is to continue with a program of measurements to extract the spin polarizabilities of the proton in the 200–350 MeV energy range. Such polarizabilities are fundamental observables of hadron structure, and are amenable to calculation with various QCD-inspired models and effective theories. Data have already been taken on three polarization observables: the asymmetries Σ_{2x}, Σ_3, and Σ_{2z}, and the results for Σ_{2x} have recently been published, along with a first independent determination of the individual proton spin polarizabilities [P. Martel et al., Phys. Rev. Lett. 114, 112501 (2015)]. The data analysis for Σ_3 is complete and a manuscript with new fits for the spin polarizabilities is in preparation. The analysis for the final asymmetry, Σ_{2z}, is not yet finished. After the final asymmetry is complete, the combination of all three will allow for an independent extraction of all four spin polarizabilities with small statistical and model-dependent systematic errors.

Proton scalar polarizabilities The data acquisition has continued for the first direct measurement of the electric and magnetic dipole polarizabilities of the proton, α^p_{E1} and β^p_{M1}. Until now, experiments relying on dispersion relation analysis have only been able to extract their sum and difference, resulting in correlated errors for the two quantities, and since the magnetic polarizability is an order of magnitude smaller than the electric one, the relative error on β^p_{M1} is large. Since the precise value of β^p_{M1} is used in other fields of physics, a more direct measurement method is needed, and a novel technique of measuring the photon beam asymmetry below the pion threshold will be used. A small amount of data which proves the principle of the new method exists, but in order to get the statistics necessary to appreciably reduce the errors, the tagging spectrometer is planned to be upgraded, and new runs will occur in 2016.

Neutron scalar polarizabilities Information on the neutron polarizabilities remains extremely fragmentary, largely due to the lack of a free-neutron target. Knowledge of the neutron scalar polarizabilities compare poorly with that of the proton, and the spin polarizabilities are almost entirely unknown. Canadians are collaborating with colleagues in Glasgow and Mainz to develop an active, high-pressure helium target for use at the centre of the CB-TAPS detector system. The elastic Compton scattering on both ^{3}He and ^{4}He will be measured, and with the help of recent theoretical work using chiral perturbation theory, the neutron scalar polarizabilities will be accurately extracted for the first time.

Timelike virtual Compton scattering on the proton Finally, a measurement of dilepton production from the proton to access the Generalized Polarizabilities (GPs) of the proton in the timelike region is planned. This is a very challenging experiment due to the extremely small cross sections involved, but the timelike proton GPs have never been measured and thus such a study would be well worth the effort. Moreover, in addition to obtaining information on the timelike GPs, new theoretical work suggests that this reaction could be used to help solve the proton radius puzzle. The proof of principle has been shown by two analyses of the dilepton production channel with the TAPS detector alone at MAMI.

3.1.2.3 Oak Ridge National Laboratory

The Hadronic Parity Violation (HPV) studies at the Spallation Neutron Source (SNS) of Oak Ridge National Laboratory consists of two experiments with Canadian involvement: NPDGamma and n^{3}He.

NPDGamma (ORNL) Manitoba, TRIUMF; India, Japan, Mexico, Switzerland, USA

The NPDGamma HPV experiment completed its work in 2014 and is currently in the final analysis stage. The central observable of this experiment's program is the weak pion-nucleon coupling constant, H_π^1. This coupling gauges the strength of the strangeness-conserving $\Delta I = 1$ neutral weak current in hadronic systems and is sensitive to modifications from strong interactions in the non-perturbative regime. In fact, the NN weak amplitudes are a good probe of the poorly understood confinement and chiral symmetry breaking dynamics of QCD. Experimental evidence of sensitivity to non-trivial QCD dynamics, through an observable like the weak NN interaction, which acts in the QCD ground state without exciting the nucleons, would make the calculation of NN weak amplitudes an essential benchmark for theories of nonperturbative QCD. The results of this NPDGamma measurement, to be released in October 2015, will surpass the precision of any other measurement of this quantity (see Fig. 3.6(a)) in a cleanly interpretable, few-nucleon system. Aside from providing a value for this coupling, NPDGamma will also provide the most precise measurement of parity violation in cold neutron capture on aluminum, which will provide new constraints on compound nuclear theoretical models.

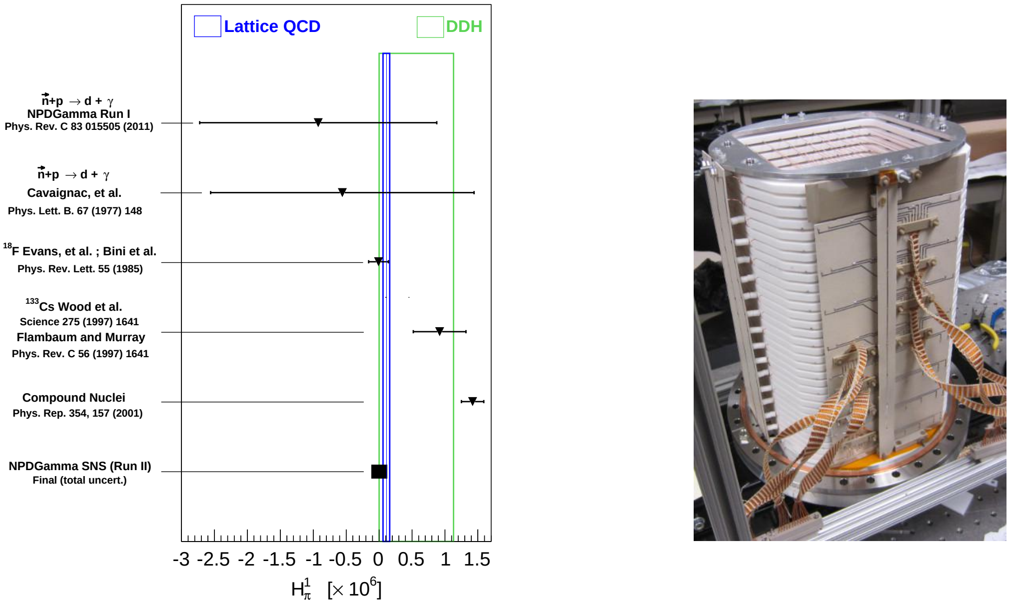
n^{3}He (ORNL) Manitoba, TRIUMF; Italy, Mexico, USA

The n^{3}He experiment measures the parity violating directional asymmetry in proton emission, in the capture of polarized cold neutrons on helium-3 in a combined target-detector wire chamber. The chamber was designed and constructed at the University of Manitoba. It was installed and commissioned in the fall of 2014 and is currently successfully taking data at the SNS. Figure 3.6(b) shows the construction of the target-detector chamber. The experiment is expected to conclude by the end of 2015.

3.1.2.4 Duke University Free-Electron Laser Facility

(DFELL) Saskatchewan; USA

The Canadian work at the Duke University Free-Electron Laser Facility (DFELL) relies on the High Intensity Source (HIGS): This Compton back scattering gamma-ray source produce photons between 2 and 100 MeV with either circular or linear polarization with energy resolution of a few percent. In recent years, several measurements of the deuteron photo-disintegration were made



(a) (b)

Figure 3.6: (a) Measurements of the weak pion-nucleon coupling constant, including the final NPDGamma precision, with the central value not yet published and arbitrarily placed at zero in this plot. The theoretical results, Lattice QCD and DDH model, are respectively from [J. Wasem, PRC 85, 022501(R) (2012)] and [B. Desplanques *el al.*, Ann. Phys. (NY) 124, 449 (1980)]. (b) The n^{3}He Target-Detector chamber being constructed.

using *Blowfish*, a neutron detector designed and developed by a collaboration between the University of Saskatchewan and the University of Virginia. It consists of 88 liquid scintillator cells configured in a spherical arrangement of 8 arms with 11 cells each that cover $\sim 1/4$ of 4π solid angle. This arrangement allows measurements of angular distributions and asymmetries of emitted neutrons and may be rotated about the beam axis to remove systematic asymmetries. This setup will be put to use in upcoming experiments at this facility.

3.1.2.5 Theoretical work in QCD and hadronic physics

There is a very active Canadian community pursuing a plethora of research topics on the theoretical aspects of QCD and of hadronic systems. These range from the theory of QCD in the extreme conditions immediately following the Big Bang, to the understanding the detailed structure of QCD bound states. Canadian theorists are established leaders in these areas of research and have an active participation in other theory and experimental groups working world-wide. Importantly, calculations involving QCD appear not only in nuclear physics, but in all computations and estimates that rely on the Standard Model such as calculating decay modes of the Higgs boson. In several cases, the overall precision is often determined by our knowledge of the strong interaction. A great opportunity exists to further strengthen and grow this program with strategic investment in HQP who can accelerate the efforts of these recognized world leaders that are often intimately linked to

Canadian experimental efforts in nuclear physics. Detailed examples of the specific efforts being pursued by Canadian QCD and hadronic matter theorists are given in section 3.5.

3.1.3 The next five years and beyond

3.1.3.1 The Thomas Jefferson National Accelerator Facility

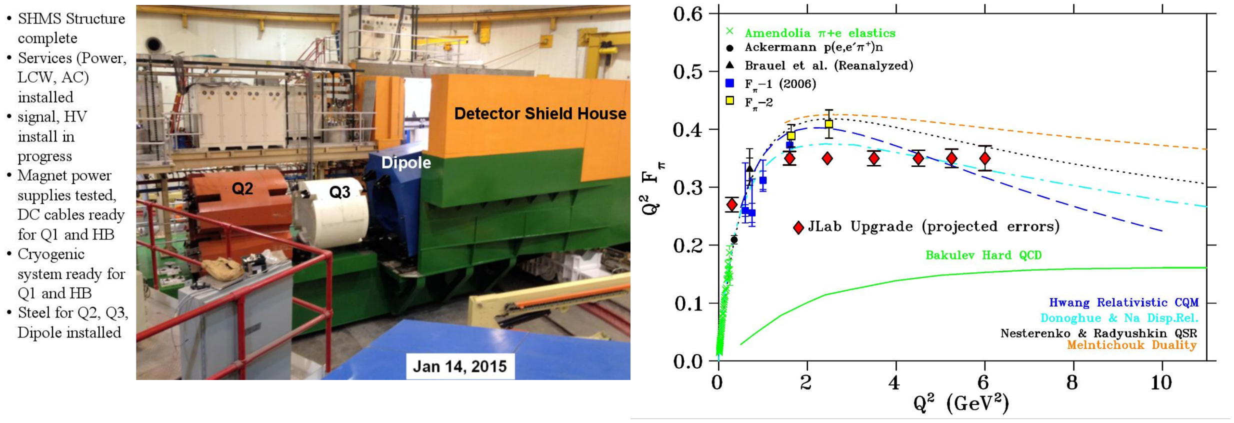
The coming years will capitalize on the considerable infrastructure investment that is the JLab 12 GeV upgrade. The experiments at this vastly improved facility involve upgraded and new detectors; they will probe the nature of QCD confinement, as well as map the transition between partonic and hadronic degrees of freedom. These research projects build on the Canadian expertise and experience, and advance Canadian leadership to a new level.

GlueX From 2016 and onwards, GlueX will be the priority in JLab Hall D, and will be the only experiment at JLab to receive the full 12 GeV electron beam to generate polarized photons in the 8-9 GeV range incident on a LH_2 target. The many hours of beam time allocated to the experiment for the period 2016-2021 will require a sustained Canadian presence at JLab. Some of the specific tasks facing that group are

- Simulations (standalone and the full HDGEANT package)
  - Shower/cluster properties & reconstruction
  - Calibration and commissioning analysis
- Physics analyses in 2016 and beyond
  - Polarized photons and partial wave analysis with boosted decision trees to disentangle J^{PC} combinations
  - Study P-wave mesons in channels such as $b_1\pi$ or $f_1\pi$ that prefer to decay into the $\eta'\pi$ over the $\eta\pi$ channel
  - Focus on reconstructing neutral final states (e.g. $\eta \to \gamma\gamma$, $\eta \to 3\pi^0$, $\eta \to 2\pi^0\gamma$)

E12-06-101 (JLab) Regina, Saint Mary's; Armenia, France, Germany, Japan, Korea, Netherlands, USA

Canadians continue to be the driving force behind measurements of the pion form factor, F_π, at increasing values of Q^2, as part of the E12-06-101 experiment at JLab. This experiment relies on the Super High Momentum Spectrometer (SHMS) in JLab's Hall C, which is to be commissioned in 2016. The actual behaviour of F_π as function of Q^2, as one transitions smoothly from the non-perturbative (long-distance scale) confinement regime to the perturbative regime, is an important test of our understanding of QCD in bound hadronic systems. Since calculations cannot yet be performed rigorously in the confinement regime, the experimental data from Jefferson Lab play a vital role in validating the theoretical approaches employed, see Fig. 3.7. There is no other existing or planned facility worldwide at which these measurements can be pursued. There is very significant interest in pushing the pion form factor measurements to as high Q^2 as possible. Beyond the approved $Q^2 = 6$ GeV^2 limit approved so far, experimental techniques need to be re-assessed. The issue is that the contribution of the "pion cloud" decreases with increasing 4-momentum



- SHMS Structure complete
- Services (Power, LCW, AC) installed
- signal, HV install in progress
- Magnet power supplies tested, DC cables ready for Q1 and HB
- Cryogenic system ready for Q1 and HB
- Steel for Q2, Q3, Dipole installed

Figure 3.7: (Left Panel) A photo showing the SHMS installation status in Hall C as of January 2015. (Right Panel) Projected data from the pion form factor experiment using the SHMS+HMS (red diamonds), in comparison to existing data and a variety of QCD-based calculations.

transfer, $-t$. Therefore, an extension of the F_{π^+} measurements to $Q^2 = 8.3$ GeV^2 is planned, using the SHMS+HMS (High-Momentum Spectrometer), and relying on improved theoretical estimates to extract the pion form factor from higher $-t$ data. This experimental study is planned for 2018-20.

E12-09-011 (JLab) Mount Allison, Regina, Saint Mary's; Armenia, Italy, USA

The charged kaon is an important second QCD test case. In the hard scattering limit, perturbative QCD (pQCD) predicts that the π^+ and K^+ form factors will behave similarly,

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2\to\infty]{} \frac{f_K^2}{f_\pi^2},$$

where f_π and f_K are the pion and kaon weak decay constants. It is thus very important to compare the magnitudes and Q^2-dependencies of both form factors. The pion elastic form factor measurements are made indirectly, by using exclusive pion electroproduction, $p(e, e\prime\pi^+)n$, to gain access to the proton's "pion cloud", and this approach has been shown to be reliable in forward kinematics. Analogously, to extract information on the kaon elastic form factor it might be feasible to sample the proton's "kaon cloud" via $p(e, e'K^+)\Lambda$: this is the purpose of experiment E12-09-011. The 12 GeV Upgrade and the SHMS will allow these studies to be performed for the first time. Owing to the fact that the statistical and systematic error demands of the K^+ measurement are less stringent than those for the π^+ measurement, this experiment has been scheduled as one of the early SHMS commissioning experiments, and is currently planned to run in the fall of 2017.

E12-07-105 (JLab) Mount Allison, Regina, Saint Mary's; Armenia, USA

Another JLab Hall C experiment, E12-07-105, is led by Canadians and is set to measure the Q^2 dependence of the longitudinal and transverse $p(e, e'\pi+)n$ cross sections. The extraction of Generalized Parton Distributions (GPDs) from hard exclusive reactions relies on the factorization of the amplitude into hard and soft processes. If factorization holds, the longitudinal cross section should be dominant and the separated cross sections should scale according to the $1/Q^n$ predictions of pQCD. This experiment will be interleaved with the pion form factor measurements, and will also begin in 2018.

PR12-12-005 (JLab) Regina; USA

Measurements of the transverse target single-spin asymmetry in exclusive π^- production from transversely polarized ^{3}He (acting primarily as a transversely polarized neutron target) shall also be pursued. This polarization observable has been noted as being especially sensitive to the spin-flip Generalized Parton Distribution (GPD) $\tilde{E}$, and factorization studies have indicated that precocious scaling is likely to set in at moderate $Q^2 \sim 2-4$ GeV^2, as opposed to the absolute cross section, where scaling is not expected until $Q^2 > 10$ GeV^2. Furthermore, this same observable has been known to be important for the reliable extraction of the charged pion form factor from pion electroproduction. If the remaining technical challenges are overcome, the experiment using the SHMS+HMS could run in the mid-2020's.

SBS (JLab) Saint Mary's; USA

The Super Bigbite Spectrometer (SBS) collaboration is a working group within the Hall A collaboration whose purpose is to ensure the successful running, analysis, and publication of approved experiments which will use all or parts of the equipment of SBS. This collaboration formulated the original scope and drove the realization of the SBS program. This collaboration includes the group of individuals who initially developed the SBS program, as well as the experiments for which this hardware is essential. The modern approach to measuring the nucleon form factors at high Q^2 involves polarization measurements, a version of which measures the polarization of the recoil nucleon. These recoil-proton polarization components are measured using a Focal-Plane Polarimeter (FPP). The SBS in JLab's Hall A features Canadian involvement, and will allow continuation of this FPP method up to $Q^2 = 12$ GeV^2 (Fig. 3.8). It is well underway to meet first use in 2018.

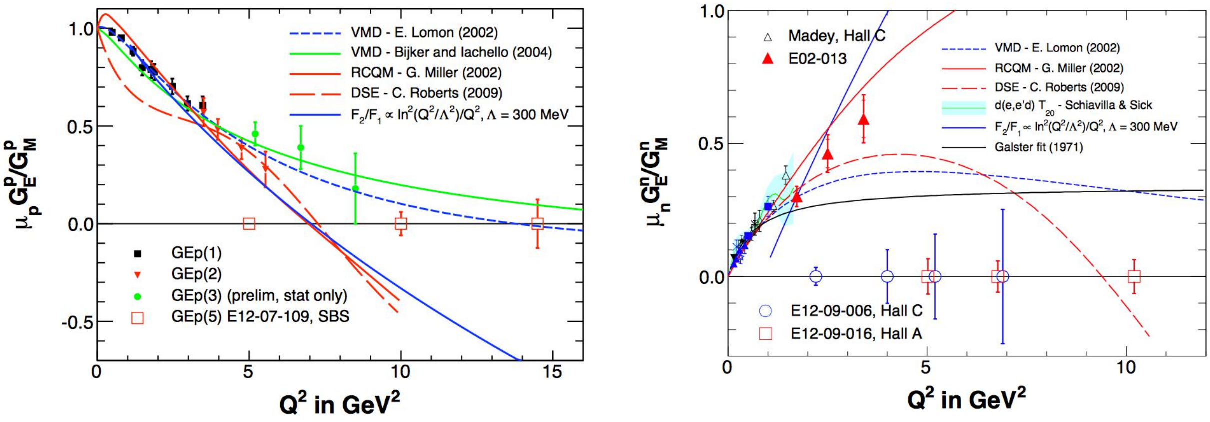


Figure 3.8: Existing data and projected errors for measurements of the ratios of the electric and magnetic form factors of the proton (left panel) and neutron (right panel). The projected errors for the measurements made within the Super BigBite project are shown by the open red squares. On the left panel are shown published results, some preliminary results from GEp(3), the projected results of GEp(5) in a 60-day. Also shown are various theoretical calculations. On the right-hand panel, together with published and preliminary results, are the projected errors of GEn(2), which is part of the Super BigBite project, and E12-09-006 with SHMS (open blue points).

E12-14-009 (JLab) Saint Mary's; USA

The JLab upgrade enables the nucleon structure studies performed in Hall A to extend to high values of Q^2, the virtual photon momentum transfer squared. The measurements of the proton and neutron electromagnetic form factors have been critical to our understanding of the proton's internal structure. As the laboratory gears up for the high Q^2 runs with the SBS, an opportunity will however exist to complete our knowledge of form factors at low Q^2, for light nuclei. The E12-14-009 experiment will extract the ratio of the electric form factor (G_E) of ^{3}He and ^{3}H from the measured ratio of the elastic-scattering cross sections at $E_{\mathrm{beam}} = 1.1$ GeV. Measurements at $Q^2 < 0.1$ GeV^2 will allow accurate extraction of G_E with minimal contributions from the magnetic form factor (G_M) and Coulomb corrections. From this data, the difference between the charge radii for ^{3}He and ^{3}H will be obtained.

3.1.3.2 Mainz Microtron

Regarding the proton spin polarizabilities experiment, the necessary experimental measurements will take approximately another two years to complete. The data analysis will continue for another few years, so work on this experiment is expected to continue to nearly the end of the next five year plan. The timeline for the pion photoproduction experiment is similar. Looking past 2020, it would appear from internal discussions at Mainz that the accelerator complex there will be winding down operations over the next 5-7 years, in favour of a new accelerator called MESA, and the program at FAIR-GSI.

3.1.3.3 The longer term: The EIC

Understanding the interior structure and the interactions of nucleons and nuclei in terms of the fundamental fields of QCD, quarks and gluons, is one of the primary goals of hadronic physics. In this context, the role and population of gluons in the nucleon and nuclear wave functions remains elusive and needs to be investigated in theory and in experiment. Of the many questions an Electron-Ion Collider (EIC) could address explicitly [arXiv:1212.1701]: How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? Where does the saturation in gluon densities set in? How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

There are currently more than one proposal for a facility of this kind, but the proposal that is probably more relevant for the Canadian nuclear physics community is that of the Electron-Ion Collider (EIC) in the USA. It will not have the energy of HERA (a former accelerator at DESY, in Hamburg, Germany), but approximately half: $\sqrt{s} \sim 166$ GeV in the current design, for electron-proton collisions. It will however be the world's first electron-nucleus collider. In that configuration, it should have a maximum energy of $\sqrt{s} \sim 90$ GeV/nucleon, will have polarization capabilities for both the electron and ion beams, and will benefit from a luminosity several orders of magnitude above that of HERA. CERN's LHeC project focuses on electron-proton collisions with energy $\sqrt{s} \sim 1.3 - 2$ TeV.

At a polarized EIC, where longitudinally polarized electrons would collide with polarized ions, many of the hadronic structure uncertainty issues that plague lower energy fixed target experiments are alleviated. Data can be obtained over a wide range of four-momentum transfer

Q^2 and Bjorken x (fraction of momentum carried by the struck quark) with high precision, making it possible to separate the vector and axial-vector quark coupling constants, with very little impact of higher-twist effects and axial-current uncertainties. In addition, the EIC will provide a unique opportunity to extract the weak-electromagnetic interference amplitude from the parity-violating asymmetry in the collisions of unpolarized electrons off longitudinally-polarized light-ions. At sufficiently high Q^2 and W^2, one can extract two independent new structure functions $g_1^{\gamma Z}$ and $g_5^{\gamma Z}$, which will provide unique new information about polarized parton densities in the nucleon, augmenting existing measurements in electromagnetic double-spin asymmetries. Studies of Q^2 evolution of these new structure functions could potentially provide new insights into the QCD structure of the nucleon. It is envisioned that the EIC will collect data with three polarized light-ion species: ^{1}H, ^{2}H and ^{3}He. It will be possible to measure both single- and double-spin asymmetries with longitudinal polarization in the neutral current process, as well as analogous asymmetries in the charged current process, thus accessing electroweak amplitudes with γ exchange, W exchange and γZ interference. Putting all these structure functions together would provide stringent new tests of the QCD structure of the nucleon and help alleviate the limiting systematic errors from poor knowledge of the electron and light-ion longitudinal polarizations.

This new facility will signal the dawn of a new era for the quantitative exploration of QCD. For instance, the contribution of gluons to the spin of the nucleon had been largely uncertain. This situation has improved, owing much to progress made in the RHIC research agenda. One of the achievements of the RHIC polarized proton collision program is a determination of the nucleon's gluon spin distribution which dominates the world data [D. de Florian *et al.*, Phys. Rev. Lett. 113, 012001 (2014)]. An EIC would be able to push measurements like these to a much higher value of energy, probing the nucleon interior with much greater spatial precision. In addition, the EIC would enable a new generation of experiments designed to map the three-dimensional structure of the nucleon, by measuring multi-dimensional distributions of partons. Also, theoretical estimates of the very high-energy limit of QCD predict the existence of a strongly-correlated gluon matter, whose behavior can be modelled in terms of an effective theory named the Color Glass Condensate (CGC).

The Canadian hadronic/QCD community is already at work, preparing its participation in detector design and development, as well as in experiment planning.

3.1.4 Summary

The research community involved in hadronic/QCD physics pursue a program that is rich and diverse. The many projects in the program aim to study QCD under all of its facets, from understanding the nature of the many-body problem at zero and finite temperatures, to mapping out the transition between hadronic and partonic degrees of freedom. Canadians have undertaken key responsibilities in their respective experimental collaborations, and have continued to make fundamental contributions to theory. In the years ahead, a specific example of the potential to access new physics is the successful 12 GeV upgrade of the Jefferson Laboratory, which has transformed that facility into a site that will provide unique opportunities to understand the nature of the strong interaction, the nucleon, and the nucleus. In addition, as new facilities like the proposed EIC enter an advanced stage of planning, the Canadian hadronic/QCD community is already at work, preparing its participation in detector design and development, as well as in experiment preparation. In order to realize the strong scientific potential of the new generation of experiments in which the Canadian hadronic/QCD community is involved and to enable a vigorous theoretical effort (see Section 3.5), a continued strong support of researchers and a strategic investment in HQP is necessary.

3.2 The structure of nuclear matter

3.2.1 Overview

The nucleus is one of the most challenging quantum many-body systems to describe. This is largely due to the fact that the primary modes of excitation (single-particle excitation, spherical vibrations, rotations of a deformed shape) all act on a very similar energy scale, meaning that all are observed in nature and become mixed together. The key to describing the diverse features of nuclear structure is to develop a robust and complete understanding of the nuclear force which acts between the constituent nucleons. This is a major challenge because of the enormous computational power required to describe the behaviour of tens or hundreds of nucleons, and the many contributions to the nuclear force which subtly change as a function of neutron and proton number, neutron-proton ratio, and excitation energy. Nonetheless, tremendous progress has been made in recent years in both developing the theoretical tools and frameworks which can make this link from QCD to nuclei, and in the acquirement of pertinent nuclear data that can challenge and drive forward the development of these theoretical calculations. Canadian researchers are at the forefront of this field of research and the many contributions and activities are described in this Chapter. With continued support and strategic investment, Canada is well positioned to make key contributions to the field of nuclear structure research in the coming years.

3.2.2 The Canadian program

3.2.2.1 Studies of neutron halos in light-mass systems

Halo nuclei probe some of the most urgent questions in nuclear physics. The classical example of a halo nucleus is ^{11}Li. In this nucleus, the two neutrons nearest the Fermi surface are weakly bound, so that their spatial wave functions are diffuse compared to stable nuclei. These properties are confirmed by a very small two-neutron separation energy (measured by the TITAN facility: [M. Smith *et al.*, Phys. Rev. Lett. 101, 202501 (2008)]) and a large inclusive reaction cross section (measured at ISAC: [I. Tanihata *et al.*, Phys. Rev. Lett. 100, 192502 (2008)]). Recently, the IRIS facility at TRIUMF-ISAC focused on the search for the soft-dipole resonance in ^{11}Li that was predicted for the last two decades but its existence was still in question. The IRIS program investigated it through the inelastic scattering using two different probes, namely protons and deuterons. The first result [R. Kanungo *et al.*, Phys. Rev. Lett. 114, 192502 (2015)] from deuteron inelastic scattering shows clear evidence of the soft-dipole resonance at the very low excitation energy of 1.03(03) MeV (See Fig. 1.3), and furthermore elucidates for the first time that this resonance has isoscalar character. This challenging experimental result was made possible by two world-unique features; the world's highest intensity of ^{11}Li radioactive beam available from TRIUMF-ISAC and the solid hydrogen/deuterium reaction targets of the IRIS facility 3.2.2.5.

A number of other light, neutron-rich nuclei exhibit halo properties, either in ground states or excited states. In the last 15 years, modern nuclear physics theory techniques, including but not limited to chiral effective field theory, momentum truncation (V_{lowK}), and no-core shell and coupled-cluster models, have evolved to provide precise predictions of the properties of these nuclei. At the same time, increasing production of these nuclei at modern radioactive beam facilities has enabled detailed measurements of their properties. TRIUMF-ISAC has been at the leading edge of these experimental studies owing to its world-leading production rates and re-acceleration of these nuclei, and halo systems have been studied in mass measurements, laser spectroscopy and nuclear reactions at ISAC. The TITAN mass spectrometer has performed a series of mass measurements of the He, Li and Be isotopes which have provided key experimental data to guide the development of the theoretical understanding of the 3-nucleon force. A recent highlight includes the direct mass measurements of the neutron-halo nuclei ^{6,8}He [M. Brodeur *et al.*, Phys. Rev. Lett. 108, 052504 (2012)]. Two TIGRESS experiments were performed to measure electromagnetic matrix elements in light nuclei. The first, on ^{10}Be [J.N. Orce *et al.*, Phys. Rev. C 86, 041303(R) (2012)], showed that the first excited state of this nucleus is prolate rather than oblate deformed, as had been predicted in some calculations. The second experiment studied ^{11}Be. This nucleus has a $1/2^-$ ground state and an excited state $1/2^-$ state at 320 keV excitation energy. The transition between these states was measured with TIGRESS and established the $E1$ matrix element to a precision of $\pm 2\%$ [E. Kwan *et al.*, Phys. Lett. B 732, 210 (2014)], a factor of 5 improvement over previous data. The laser-spectroscopy group has developed the technique of zero-field β-detected nuclear quadrupole resonance (β-NQR) and used it for the first time to make a precise measurement of the ratios of the quadrupole moments of ^{11}Li and ^{9}Li [A.Voss *et al.*, J. Phys. G. 38, 075102 (2011)]. This new technique has an order-of-magnitude improvement in precision over previous methods bringing the experimental data to a sufficient quality to challenge state-of-the-art theory calculations.

These measurements with TITAN, β-NQR and TIGRESS provided demanding tests of modern *ab initio* nuclear structure calculations, and involved a close collaboration between the experimental teams and the nuclear theory group at TRIUMF who are world experts in *ab initio* no-core shell model calculations.

An additional ^{11}Be experiment focusing on the scattering angular distribution led by Madrid-CSM collaborators used γ-ray detection with TIGRESS to select inelastic scattering events. This experiment focused on the scattering mechanism for this weakly-bound system, in particular the role of interference from the single excited state and continuum to this process. The halo nature of excited states in ^{10}Be [D. Smalley *et al.*, Phys. Rev. C 89, 024602 (2014)] and ^{12}Be [R. Kanungo *et al.*, Phys. Lett. B 682, 391 (2010)] have also been studied with TIGRESS. With the combination of the newly operational GRIFFIN and DESCANT spectrometers, a new era of high-efficiency $\beta-\gamma-n$ coincidence studies tagged by specific neutron emission branches will become possible at ISAC-I, providing an opportunity for definitive β-decay experiments on the prototypical 2-neutron halo nucleus ^{11}Li, and extending this research program to the decay of more exotic halo nuclei such as ^{14}Be. As ISAC continues to provide the highest intensity source of these radioactive ion beams of light nuclei, this research program will continue to be exploited to test and help develop modern *ab initio* nuclear structure models.

3.2.2.2 Evolution of nuclear shell structure

In the last decade, much of the nuclear physics program at radioactive ion beam facilities has been driven by the finding that major shell gaps disappear and new shell gaps appear for exotic nuclei with large proton or neutron excess [R. Krücken, Cont. Phys. Vol. 52, 101120, (2011)]. This finding is not only of fundamental importance for our global understanding of the atomic nucleus as a quantum many-body system, but also has a major impact on our understanding of nucleosynthesis. As an example, the question of the "quenching" of the N=82 shell gap for neutron-rich nuclei below ^{132}Sn largely determines the theoretical characteristics of the A=130 r-process abundance peak. To disentangle the various possible r-process phenomena and their impact on the elemental abundance, a robust understanding of nuclear shell evolution is needed (Section 3.3.2.2). Currently, experimental knowledge of neutron-magic r-process "waiting point" nuclei below ^{132}Sn and ^{208}Pb is sparse. Much of our understanding of shell evolution is thus based on experimental data in lighter nuclei. A textbook example is the "Island of Inversion" around ^{32}Mg, where experimental data suggest a weakening of the N=20 shell gap. The γ-ray spectroscopy group working at ISAC has made significant contributions to this understanding through both, β decay experiments with the 8π spectrometer at ISAC-I studying the excited state structure of ^{32}Mg, and Coulomb excitation experiments with TIGRESS at ISAC-II studying the transition to the Island of Inversion in ^{29}Na.

The future experimental research program in the field of nuclear shell evolution will concentrate on two major outstanding questions:

- What is the microscopic origin of the shell evolution observed in light and medium-mass nuclei?
- Are the same mechanisms of shell evolution present in "waiting point" nuclei below ^{132}Sn or neutron-rich nuclei beyond ^{132}Sn participating in the r-process?

Concerning the first point, the tensor component of the nuclear force was suggested to play a dominant role in understanding shell evolution in the Island of Inversion around ^{32}Mg. On the other hand, the characteristic behaviour of weakly-bound orbits with small angular momentum suggests an interpretation of shell evolution as a nuclear Jahn-Teller effect. The situation is complicated by the finding that measured cross sections after two-neutron transfer towards ^{32}Mg are not consistent with the presence of an Island of Inversion, i.e. dominant intruder configurations in the ground state of nuclei at N=20, as found in most recent shell model calculations. Indeed, collective models support a more complicated scenario of strongly mixed spherical and deformed structures.

The strong deformation which characterizes Na and Mg isotopes at and around N=20 in the region of the Island of Inversion can also be investigated with ground state masses. The TITAN mass measurement campaign [A. Chaudhuri *et al.*, Phys. Rev. C 88, 054317 (2013)] has led to the first direct mass measurements of these neutron-rich isotopes as well as of bordering Al isotopes. These measurements are also noteworthy for the very short half-lives, as low as 13 ms for ^{32}Na, and cannot be performed at any other Penning trap mass spectrometer world-wide.

These mass measurements have identified two irregularities. First ^{32}Mg exhibits the lowest shell strength of any magic nuclide. The second anomaly is the crossover of the two-neutron separation energy S_{2n} of ^{33}Mg and ^{34}Al, an occurrence found nowhere else on the mass surface. Large-scale shell model calculations of the binding energy and S_{2n} are in good agreement with the TITAN data. Calculated energy gains from correlations peak at almost 3.5 MeV at N=21 in the Mg isotopes; the same effect is weaker in the Al isotopes ($<$ 2 MeV) and delayed (N=24). The offset between maximal gains leads to the S_{2n} crossover at N=21 as shown in Fig. 3.9.

Further efforts are being made to pinpoint the mass of the 1^+ state of ^{34}Al, and such a measurement may indicate the spin-parity of nuclide's ground state. Future mass measurements of ^{36,37}Al are needed to confirm the expected deviation from the evaluated mass values, which may place these isotopes within the Island of Inversion.

Mass measurements performed at TRIUMF using the TITAN Penning trap mass spectrometer greatly help revealing detailed information of the effective interaction of nucleons, by providing access to the nuclear binding energies. Using this system it was possible for the first time to determine the masses of the very neutron-rich Ca and K isotopes [A.T. Gallant *et al.*, Phys. Rev. Lett. 109, 032506 (2012)] and make interesting comparisons to state-of-the-art theory. Fig. 3.10 shows this for the calcium isotopes. The experimental results found for ^{52}Ca deviated by almost 2 MeV from the previous measurements but agree well with the predictions from modern theory where 3N forces were included. Following these interesting findings, the ISOLTRAP collaboration

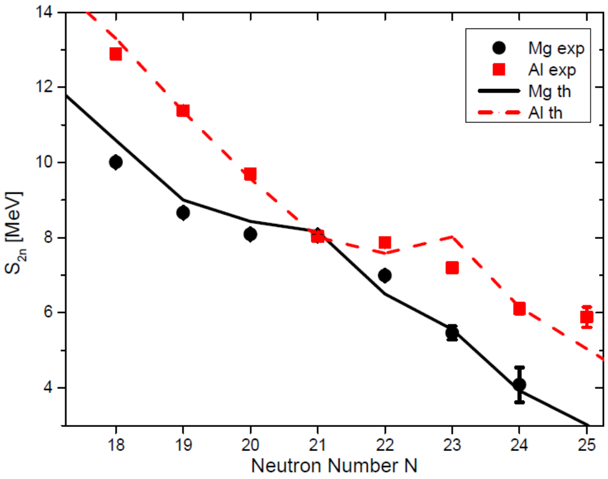


Figure 3.9: Two-neutron separation energy for the isotopes in the island of inversion as measured by TITAN and from theoretical calculations using the Monte Carlo shell model based on the quantum Monte Carlo diagonalization method.

at ISOLDE/CERN was able to confirm the TITAN measurements and further advance the limits of precision mass measurements out to ^{54}Ca using a new multi-reflection time-of-flight mass spectrometer. The new Ca masses are in excellent agreement with modern theoretical predictions (as shown in figure 3.10) performed by the TRIUMF theory group and others. A new shell closure at N=32 is now unambiguously established.

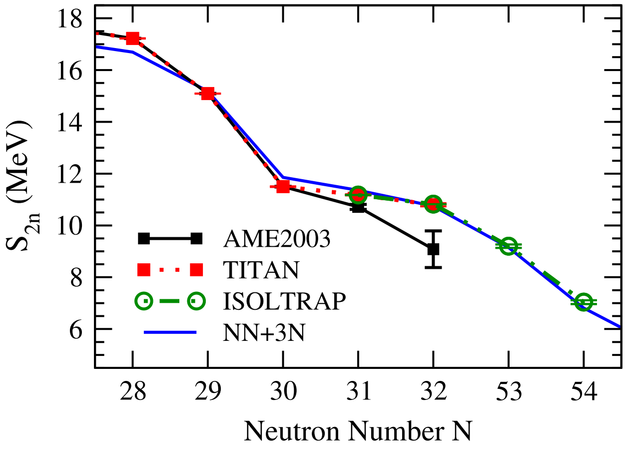


Figure 3.10: Two-neutron separation energy (difference of binding energies) of neutron-rich Ca isotopes: measurements by TITAN and ISOLTRAP in comparison to the atomic mass evaluations of 2003 and state-of-the-art theory calculations (blue line).

The TIGRESS and GRIFFIN instruments, together with their auxiliary detectors, at ISAC offer ideal opportunities to gain new insights into the evolution of nuclear shell structure in light and medium-mass nuclei. Studies of nuclei in and around the Island of Inversion through high-efficiency $\beta - \gamma - n$ coincidence measurements, including $\gamma - \gamma$ angular correlation measurements to establish definite spin-parity assignments for excited states in the daughter nuclei, were a major focus of the first GRIFFIN experimental campaign in the summer of 2015 with neutron-rich beams of Na and Mg isotopes provided by ISAC-I. These GRIFFIN + DESCANT $\beta - \gamma - n$ coincidence measurements will then be extended to heavier nuclei, including the region of intense current interest in the neutron-rich Ca isotopes between ^{52}Ca and ^{54}Ca, where new doubly-magic nuclei may result from the development of significant shell gaps at N=32 and 34. Detailed studies of these isotopes with GRIFFIN and DESCANT, in combination with theoretical work led by members of the TRIUMF theory group [J.D. Holt *et al.*, Phys. Rev. C 90, 024312 (2014)], have the potential to lead to breakthroughs in our understanding of the 3-nucleon forces in intermediate mass nuclei and their role in the evolution of nuclear shell structure far from stability.

Complimentary information on shell structure evolution is obtained from experiments with accelerated radioactive beams from ISAC-II. The newly developed tritium target, together with SHARC and TIGRESS, can be used to study two-neutron transfer into ^{30}Mg. For this reaction, the ratio of 0_1^+ to 0_2^+ population is predicted to be at an extreme, yielding the most precise input into model calculations. A key ARIEL experiment will be the two-neutron transfer into ^{32}Mg to measure the lifetime of the 0_2^+ state and quantify the mixing between normal and intruder configurations. This study is beyond the reach of present ISAC beam intensities. Due to its predicted long lifetime (10-100 ns), this can be achieved via a direct timing measurement with the available LaBr$_3$ detectors coupled to TIGRESS. Even shorter lifetimes can be measured with the Doppler Shift Attenuation Method (DSAM) using the high position sensitivity of TIGRESS. Such a DSAM experiment is planned following the ^{29}Mg(d,p) reaction to populate the deformed, shape-coexisting, excited band in ^{30}Mg and measure the intra-band B($E2$) values. For even-even nuclei at closed proton (neutron) shells, the magnetic moment of the first excited 2^+ state is predicted to have large negative (positive) values. Magnetic moment measurements are thus also a powerful tool to trace shell evolution. In the case of N=20, the measurement of $g(2_1^+)$ in ^{32}Mg after Coulomb excitation would answer the question if intruder configurations are indeed dominant in its ground state. Thus, a new magnetic moment setup for TIGRESS is planned, utilizing the transient field method.

Francium, the heaviest alkali element, has a simple nuclear structure with just 5 valence protons outside an inert Pb core. Extensive studies were previously carried out on $^{228-204}$Fr. The neutron deficient Francium isotopes, ^{204,206}Fr, have long been postulated to contain at least one and possibly two long lived isomeric states. Recent work at ISAC [A. Voss *et al.*, Phys. Rev. C91, 044307 (2015)] has shown that these two isotopes have very similar structures, each containing two long lived isomeric states. In the most recent experiments a new technique of frequency modulation was developed at TRIUMF, which enabled the sensitivity to make these measurements shown in Figure 3.11. Model independent determination of the nuclear spins for all of these state in addition to the ground state of ^{205}Fr has allowed for the extraction of the nuclear moments and changes in mean squared charge radii for all states seen. These result show that the remarkable single particle nature observed above the Pb isotopic chain is starting to break down with the onset of collectivity around N=118.

Looking further to the future, the ARIEL upgrade will provide experimental data on shell evolution beyond ^{132}Sn and for waiting point nuclei at N=82 below ^{132}Sn. The goal is to gain first information on the excitation energies, spins and spectroscopic factors of low-lying excited states in nuclei such as ^{137}Sn and ^{131}Cd. As an example, the evolution of spin-orbit partners such as $f_{7/2} - f_{5/2}$ and $p_{3/2} - p_{1/2}$ can be traced after one-neutron transfer reactions. Such studies are of fundamental importance for our understanding of nucleosynthesis and will also provide insight into

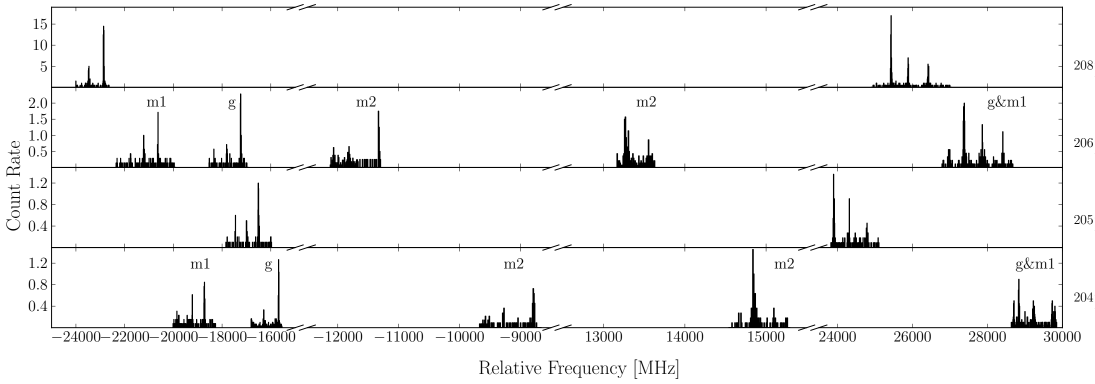


Figure 3.11: Experimentally measured hyperfine structure of the ground state and isomeric states in neutron-deficient Fr isotopes from the collinear laser spectroscopy experiments at TRIUMF using the newly-developed frequency modulation technique.

the long standing question of the evolution of the nuclear spin-orbit interaction in heavy, neutron-rich nuclei. However, even at ARIEL, beam intensities on target will be limited to a few kHz for these very neutron-rich nuclei. As detailed in Section 3.2.2.5, a new gas target Si tracker detector optimized for these ARIEL experiments at ISAC-II is in the planning stages.

3.2.2.3 Studies of nuclear collectivity, shape coexistence, and shape transitions

One of the driving questions in nuclear physics deals with the emergence of simple patterns that are often observed in complex nuclei. Although the nucleus is composed of many (sometimes hundreds) of individual protons and neutrons which occupy single-particle energy levels, collectivity is a global behaviour of the nucleus, considered analogous to a liquid drop. Deformations of this liquid drop are possible and may take the form of collective vibrations or, if there is a permanent elongation along one of the axes, rotations. Combinations of vibrational and rotational motion are also possible, and unlike the case in molecules, the similarity of the excitation energy scale can make disentangling the excitation modes difficult. Many of the collective phenomena observed in nuclei cannot yet be predicted from the underlying nucleon-nucleon (including 3N) interactions. Experimental studies are thus vital in elucidating the nature of collective excitations, especially when data can be obtained using a variety of probes. The wide variety of collective excitations in nuclei, from “giant” resonances that involve the response of the nucleus as a whole to the softer surface modes that (typically) involve only the valence nucleons, provide a rich spectrum of possible states. In the low excitation energy region, it is usually the surface quadrupole and octupole modes that dominate. Gamma-ray spectroscopy is one of the most important tools for investigating these modes, which may be populated in reactions such as Coulomb excitation involving accelerated beams from the ISAC-II facility and studied with the TIGRESS spectrometer, or populated in β-decay involving non-accelerated beams from the ISAC-I facility and studied with GRIFFIN and its associated detectors.

Despite over 60 years since the development of the collective model by A. Bohr and B. Mottelson, difficulties remain in understanding its true underlying structure. For example, for decades it was accepted that when moving away from closed shells, where the excitation spectrum can be understood in terms of the occupation of shell model configurations by individual nucleons, a region of nuclei possessing multi-phonon quadrupole vibrations about a spherical shape would be encountered, before giving way to permanently deformed nuclei. The Cd, Pd, and Ru nuclei were often used as prime examples of this vibrational behaviour, with some studies claiming up to 5- and 6-phonon excitations. Detailed spectroscopy following β-decay performed with the 8π spectrometer at ISAC of ^{110,112}Cd [K.L. Green *et al.*, Phys. Rev. C 80, 032502(R) (2009); P.E. Garrett *et al.*, Phys. Rev. C 88, 044304 (2012)], however, revealed that even at the 3-phonon level the decay patterns of the states possessed serious deviations from the expectations for harmonic vibrations. Further, the properties of excited states in ^{110}Cd more closely resemble those of a γ-soft rotor, rather than a spherical vibrator. In fact, when examining detailed systematics in the Cd-Sn region, robust examples of vibrators were found to be lacking [P.E. Garrett and J.L. Wood, J. Phys. G 37, 064028 (2010)]. The conclusions reached from these β-decay studies were further supported by measurements of single-neutron-transfer reactions at the Maier-Leibnitz Laboratorium in Garching, Germany, where results [D.S. Jamieson *et al.*, Phys. Rev. C 90, 054312 (2014)] of the ^{111}Cd(d,p)^{112}Cd reaction proved conclusively the incorrectness of the assignment of the 5^- member of the two-phonon quadrupole-octupole coupled states, despite its enhanced transition rate to the 3-octupole state, casting doubt on the appropriateness of the multi-phonon description for heterogeneous excitations as well.

Capitalizing on the success of the studies with the 8π spectrometer at ISAC, these investigations will be extended away from the stable nuclei towards both the neutron deficient Cd isotopes, approaching N=50, and the neutron-rich regions approaching N=82 using β-decay and the new GRIFFIN spectrometer. These studies will provide high-quality spectroscopic data to study the evolution of collectivity, especially into regions where shell model calculations are now possible.

Once believed to be a rather exotic phenomenon, shape coexistence now appears to be much more widespread, and may, in fact, be the norm rather than the exception [K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011)]. This is highlighted by the recent study [A. Chakraborty *et al.*, Phys. Rev. Lett. 110, 022504 (2013)] of ^{94}Zr, via the decay of ^{94}Y with the 8π spectrometer, in which the observation of a single, low-energy transition connecting the 2_3^+ level to the 0_2^+ level revealed the existence of a deformed shape-coexisting band in the "spherical" ^{94}Zr, as shown in Fig. 3.12. This result demonstrated the role that excitations across subshell closures play are analogous to the role that excitations across major shells play; the increased number of proton- neutron interactions leads to structures with increased deformation. Studies of shape coexistence throughout the Sr, Zr, and Mo nuclei are now envisioned, taking advantage of the superior performance of the GRIFFIN spectrometer to study the region of rapid changes in the structure of the ground state from the more spherical nuclei with $N \geq 58$, to more deformed nuclei with $N \geq 60$.

With the current research into the nature of collectivity in more-spherical nuclei, and the debate over the existence of multi-phonon excitations, it is also natural to question the nature of vibrations about deformed shapes, namely the β and γ vibrations. The existence of β vibrations has been questioned for some time [P.E. Garrett, J. Phys. G 27, R1 (2001)], but γ vibrations appear to be a rather robust excitation mode. However, it has recently been questioned if the lowest $K^\pi = 2^+$ band arises from a non-axial rotational mode, rather than a γ-vibrational mode. The Interacting Boson Model, on the other hand, predicts a deep connection between the β and γ modes such that there should be an enhanced $E2$ transition between them. Despite these questions, the detailed spectroscopic data do not exist to differentiate between the alternative models. To address this issue, a systematic study of the $^{160-174}$Er isotopes through the β decays of Tm and Ho with GRIFFIN will be pursued.

An additional area of nuclear collectivity and shape evolution research is the study of octupole

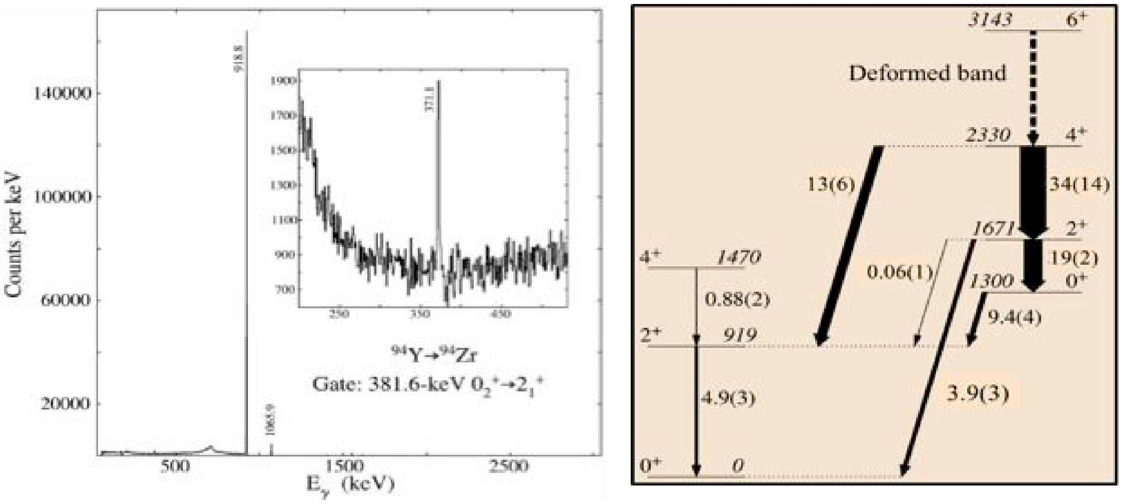


Figure 3.12: Results from the study of ^{94}Zr via the β decay of ^{94}Y with the 8π Spectrometer at ISAC. The panel on the left displays a portion of the γ-ray coincidence spectrum with the 382-keV transition from the 0_2^+ level. The inset reveals the existence of the 371-keV transition from the 2^+ level at 1671 keV to the 0^+ level at 1300 keV. The measurement of the branching ratio enabled the determination of the B($E2; 2^+ \to 0^+$) of 19±2 W.u., firmly identifying the sequence of levels as a deformed shape co-existing band. From [A. Chakraborty *et al.*, Phys. Rev. Lett. 110, 022504 (2013)].

collectivity in neutron-rich odd-A isotopes of Rn. These isotopes, in particular ^{221,223}Rn, have been suggested as candidates for a sensitive search for new CP-violating fundamental interactions in nature through precision electric dipole moment (EDM) measurements due to large (order 1000) predicted enhancements in the atomic EDMs of atoms with octupole deformed nuclei. The predicted EDM enhancements for these isotopes, however, depend sensitively on their nuclear structure, which is virtually unknown. Only one excited state, without a firm spin-parity assignment, has been observed in ^{221}Rn and no excited states have yet been identified in ^{223}Rn. Detailed nuclear structure studies of ^{221,223}Rn will be performed via high-efficiency $\beta-\gamma$-X-ray-e -coincidence measurements with GRIFFIN and its auxiliary detection systems following the β decay of ^{221,223}At.

Nuclear transition strengths are a sensitive and stringent test of nuclear models which provide insight to the underlying configurations involved in nuclear excitations, especially in the study of nuclear collectivity, shape coexistence, and shape transitions. To take advantage of the high-quality accelerated radioactive ion beams provided by the ISAC-II facility, a powerful suite of ancillary detection systems has been developed to enable the determination of nuclear transition strengths using the TIGRESS spectrometer.

The SHARC silicon barrel is used to detect charged particles with excellent energy and angular resolution. In combining this array with TIGRESS for the detection of γ rays, Coulomb excitation of the radioactive beam nucleus can be used to determine the electric quadrupole ($E2$) transition strength between the ground state and the first 2^+ excitation. This transition strength is a key measure of the nuclear collectivity of the nuclear ground state and is closely related to nuclear structure evolution. The collective nature of excitations in the neutron deficient Sr isotopes will be examined at ISAC-II using TIGRESS and SHARC in the near future.

The TIGRESS integrated plunger (TIP) allows for the determination of $E2$ strengths through the measurement of the parent state lifetime. This technique can be applied to excited states which are not easily accessed by Coulomb excitation and therefore extends the range of transition strengths which can be accessed by the TIGRESS spectrometer. Studies are planned in the neutron-deficient A=70 region of the nuclear chart, starting with ^{68}Se, where shape coexistence has been identified. Transition strength measurements using the TIP and TIGRESS setup in this region will shed light on the underlying configurations responsible for this behavior.

The SPICE detector is used with TIGRESS to detect internal conversion electrons and γ rays simultaneously to allow the determination of electric monopole ($E0$) transition strengths. These transition strengths are a very sensitive probe of the quantum mechanical mixing between shape-coexisting configurations. When combined with a knowledge of the $E2$ transition strengths a full picture of shape coexistence can be established. SPICE and TIGRESS will be used to determine $E0$ transition strengths in the neutron-deficient Krypton isotopes where a coexistence between oblate and prolate structures has been suggested in previous experiments looking at excited state energies and $E2$ transition strengths. These studies will then be extended to the N=90 isotones.

In addition to transition strengths, the degree of occupation of the various single-particle energy levels is important knowledge with which to understand the evolution of excitations around regions of shape coexistence. Such investigations are made possible with the SHARC and TIGRESS setup using single-nucleon and pair transfer reactions for which studies have recently been carried out in the neutron-rich Sr isotopes. The data are presently being analyzed, and these results will be complimented by $E2$ transition strength measurements using the TIP and TIGRESS setup, planned for 2015. The $E0$ transitions strengths in these nuclei have been measured using electron and γ spectroscopy with the PACES and 8π experimental setup, and these studies will be extended to the more neutron-rich isotopes using GRIFFIN.

3.2.2.4 Canadian effort in nuclear structure theory

The development of theoretical models to describe atomic nuclei has emerged as a particular strength in Canada over the past 5-10 years. Two additional faculty members have been attracted to Canadian institutions during the past 5 years which has established Canada as a centre for world-leading efforts in this field. A great opportunity exists to further strengthen and grow this program with strategic investment into HQP who can accelerate the efforts of these recognized world leaders at the forefront of an exciting and fast-moving discipline that is intimately linked to Canadian experimental efforts in nuclear physics.

The theory groups at TRIUMF and the University of Guelph have been developing the capability to theoretically describe light- and medium-mass nuclei as systems of nucleons interacting by forces rooted in the fundamental theory of strong interactions, QCD. Using a low-energy expansion of QCD, namely chiral effective field theory (χEFT), one can derive forces among nucleons and their interactions with external probes in a consistent way. Studies in light- and medium-mass nuclei are crucial to test such a theory and allow cross-fertilization with experiments performed both at TRIUMF and elsewhere. Detailed examples of the specific efforts being pursued by Canadian nuclear structure theorists are given in section 3.5.

3.2.2.5 Experimental facilities needed for this work

ISAC and Future ARIEL facilities at TRIUMF The Isotope Separator and Accelerator (ISAC) and the future ARIEL facility are some of the world's most powerful sources of rare-isotope beams. These facilities are essential to the nuclear structure research and the various experimental setups described in this section. The details of these facilities are discussed in Sec. 4.1.1.

GRIFFIN (TRIUMF) Guelph, SFU; USA

GRIFFIN is a new high-efficiency γ-ray spectrometer for the decay spectroscopy research program with low-energy ($\sim$30 keV) radioactive ion beams from the ISAC-I facility. GRIFFIN, shown in Fig. 3.13, is comprised of 16 large-volume "clover-type" high-purity germanium (HPGe) γ-ray detectors, each of which contains 4 HPGe crystals close-packed in a four-leaf clover geometry, with signal processing provided by a custom-designed, state-of-the-art digital data acquisition system designed to provide both the high precision required for fundamental symmetries research and the high data throughput required for experiments with intense rare isotope beams from ISAC/ARIEL. The first phase of the GRIFFIN project, with a total project cost of \$8.99M, was funded jointly by CFI, TRIUMF, and the University of Guelph over a 4-year period from 2011-2015. Initial GRIFFIN development proceeded in parallel with the operation of the 8π Spectrometer, which supported the decay spectroscopy research program at ISAC between 2003 and 2013. In January 2014, the 8π spectrometer was relocated to the Nuclear Science Laboratory at Simon Fraser University, and GRIFFIN installation at ISAC-I began. First "early implementation" experiments with GRIFFIN were completed in the autumn of 2014, and the full 16-detector GRIFFIN spectrometer is now completed and began scientific operation at ISAC in the summer of 2015. GRIFFIN provides a factor of 300 - 500 (depending on the γ-ray energy) increase in $\gamma - \gamma$ coincidence detection efficiency compared to the 8π spectrometer and will revolutionize the decay spectroscopy program at ISAC, providing sensitivity to the most exotic rare isotope beams with intensities as low as 0.01 ions/s and exploiting the full range of extremely neutron-rich beams that will be provided by the ARIEL facility. This sensitivity of the device will be further enhanced by the addition of Compton and background BGO suppression shields which will be funded through a CFI award in the 2015 competition with matching funds provided by the Ontario MRI and BC KDF.

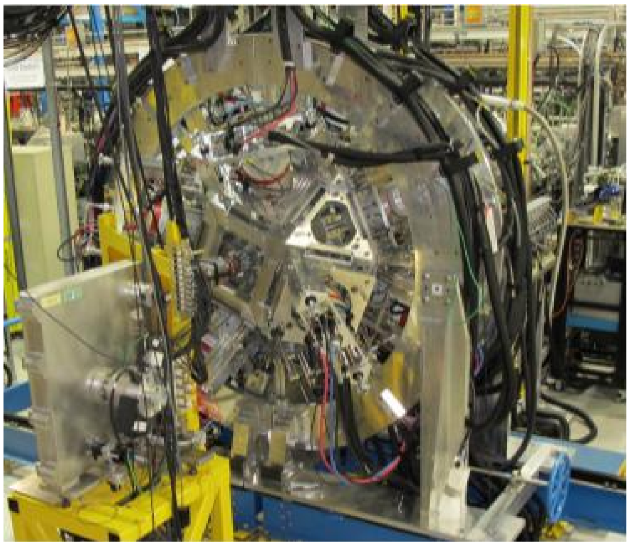


Figure 3.13: Photograph of the GRIFFIN facility at TRIUMF-ISAC.

GRIFFIN incorporates a powerful suite of auxiliary devices and detection systems that have been developed by the γ-ray spectroscopy group through funding provided by NSERC RTI-1 grants. These include an in-vacuum tape transport system to remove long-lived daughter and contaminant activities from the view of the detectors, the Scintillating Electron Positron Tagging Array (SCEPTAR) comprised of 20 thin plastic scintillators for coincident β particle detection, the Pentagonal Array for Conversion Electron Spectroscopy (PACES) comprised of 5 liquid nitrogen-cooled Si(Li) detectors for conversion electron and α particle detection, and an array of 8 $LaBr_3$ detectors for fast γ-ray timing measurements. GRIFFIN can also be coupled with the $2.0M CFI-funded DESCANT neutron detector array (Section 3.2.2.5) to provide a new high-efficiency β-γ-n coincidence detection capability for β-delayed neutron emission studies at ISAC. The combination of the rare isotope beams available from ISAC, the very-high γ-ray detection efficiency of GRIFFIN, and this versatile suite of auxiliary detection systems represents one of the world's most sensitive facilities for nuclear decay spectroscopy research with low-energy radioactive ion beams.

TITAN (TRIUMF) Calgary, Manitoba, McGill, SFU

TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science) is a unique ion trap experiment, currently consisting of five individual ion traps coupled together: an RFQ cooler and buncher, a Multi-Reflection TOF isobar separator and spectrometer (which will be installed soon), an Electron Beam Ion Trap, an Electron Plasma Cooler trap, and a precision Penning trap. Fig. 3.14 shows a photo and the schematic set-up of the TITAN system at ISAC. This one-of-a-kind setup has the fastest beam preparation and measurement cycle for on-line precision mass measurements (by an order of magnitude, with a duty cycle time of 5 ms, hence providing access to isotopes with $T_{1/2} \gtrsim 5$ ms), it is the only system in the world to provide highly charged ions, which boost the precision by one to two orders of magnitude (depending on the charge state and Z of the isotope). TITAN started in 2003 originally funded for equipment and project through an NSERC RTI, and later augmented with additional equipment from CFI and NSERC SAP RTI. The operation of the system is supported in Canada through NSERC SAP project grants. International partners have contributed as well and the estimated total capital investment in TITAN to date is $4.5M.

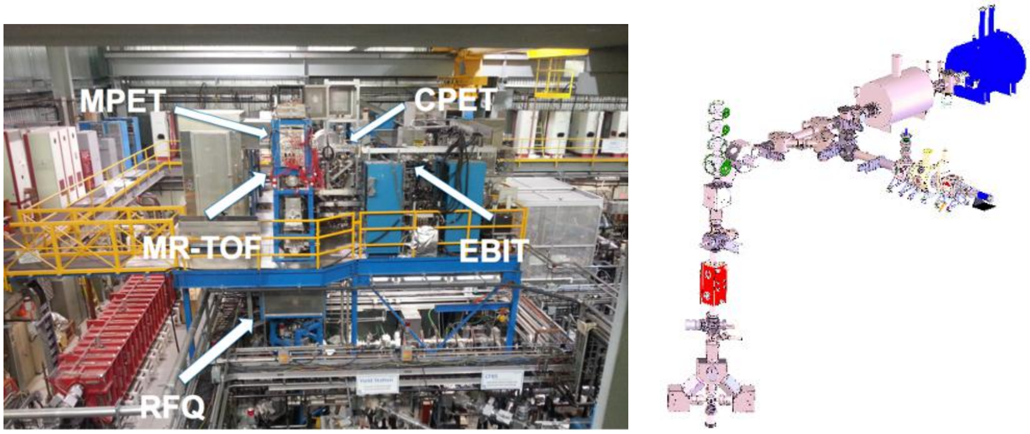


Figure 3.14: The TITAN facility at TRIUMF-ISAC-I.

The core piece of the TITAN setup is the Penning trap mass spectrometer. Penning traps are the most precise devices to measure masses reaching an accuracy of $\delta m/m < 10^{-12}$ for stable species. The precision of the mass measurement in a Penning trap is given by the inverse of the excitation time T_{RF}, and the following applies:

$$\frac{m}{\delta m} \propto \omega_c T_{RF} \sqrt{N} = \frac{qB}{m} T_{RF} \sqrt{N}, \tag{3.1}$$

where N is the number of interrogated ions, B is the magnetic field strength, and q/m is the charge-to-mass ratio. Hence the precision is directly proportional to the charge state of the ion q. Ideally, one would try to increase the excitation time as much as possible. However, this is limited in the case of short-lived isotopes by the decay half-life of the ion. Similarly, increasing the magnetic field will give an increase in precision, yet the improvement is limited by the current magnet technology. The TITAN setup is the first online system worldwide to utilize the significant increase in the charge q of the measured ion to improve the accuracy.

Collinear laser spectroscopy (TRIUMF) McGill; UK

The laser-spectroscopy group has developed the technique of zero-field β-detected nuclear quadrupole resonance (β-NQR) and used it for the first time to make a precise measurement of the ratios of the quadrupole moments of ^{11}Li and ^{9}Li. Optical pumping with circular polarization aligns the nuclear spin either in, or opposed to the beam direction. The beam of Li^+ ions is then guided so that the polarization is transverse to the beam direction, and implanted in a $SrTiO_3$ crystal. Beta-decay asymmetry is observed as an RF field is applied to the crystal. When the RF frequency matches the NQR crystal frequency, spin precession destroys the polarization and the decay asymmetry vanishes. Measurement of the NQR frequencies for the two isotopes then provides the measured ratio. This new technique has an order-of-magnitude improvement in precision over previous methods.

General Purpose Station (GPS) gas proportional β counter and tape transport system (TRIUMF) Guelph

A 4π continuous flow gas proportional β counter and tape transport system for high-precision β decay half-life measurements is operated on an ISAC-I low-energy beamline referred to as the General Purpose Station (GPS). High-precision β-decay half-life measurements have been carried out at ISAC-I since 1999 by direct β counting using a technique that was first developed at the Chalk River Laboratories. Although the measurements are simple in principle, great care must be taken to achieve the precision (0.01% - 0.05%) required for superallowed β emitters whose half-lives range over 3 orders of magnitude from 69 ms to 70 s. This facility has measured a number of the superallowed β emitter half-lives to the greatest precision achieved experimentally.

TIGRESS and ancillary detectors (TRIUMF) Guelph, Saint Mary's, SFU; France, Spain, UK, USA

TIGRESS is an array of 16 Compton-suppressed 32-fold segmented clover-type HPGe γ-ray detectors that was funded by an \$8.06M NSERC RTI-3 grant over the 6-year period from 2003 - 2009, and has been augmented by more than \$2.0M of associated detectors funded through NSERC RTI and CFI awards. TIGRESS is designed for in-beam γ-ray spectroscopy with the accelerated radioactive ion beams provided by the ISAC-II superconducting heavy ion linear accelerator at energies approaching or beyond the Coulomb barrier. All signals from the TIGRESS HPGe and bismuth germinate (BGO) suppressor detectors are read out by 100 MHz 14-bit custom-built digitizers and the captured position-dependent signal waveforms, together with the 32-fold segmentation of the outer contacts of the HPGe detectors, enable the precise translation of the γ-ray energies measured by TIGRESS into the rest frame of the recoiling nucleus.

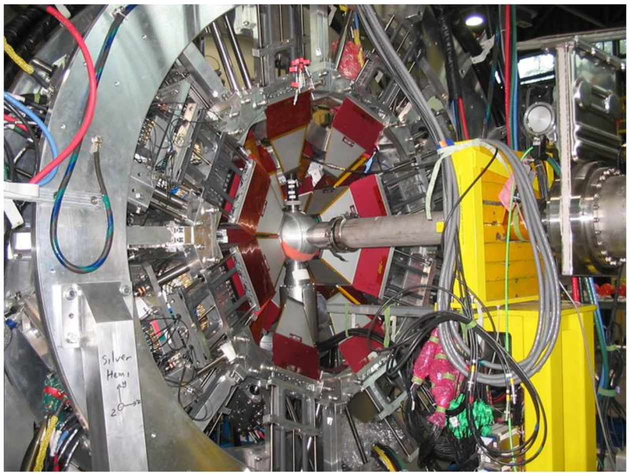


Figure 3.15: Photograph of the TIGRESS spectrometer at TRIUMF-ISAC-II.

As with GRIFFIN, the sensitivity of TIGRESS is dramatically enhanced through its coupling with a suite of specialized charged-particle and neutron detector systems that can be tailored to the specific reaction or physics under study. These TIGRESS auxiliary detection systems include:

- the Bambino detector, comprised of two 24×32 fold segmented annular "CD-type" Si detectors, developed by collaborators from Lawrence Livermore National Laboratory and the University of Rochester and optimized for Coulomb excitation experiments with TIGRESS,
- the Silicon Highly-segmented Array for Reactions and Coulex (SHARC), comprised of up to 2000 channels of double-sided silicon strip detectors (DSSDs) with nearly 4π solid angle coverage around the reaction target at the centre of the TIGRESS array, developed by collaborators from the University of York in the United Kingdom and optimized for light charged particle detection in single- and two-nucleon transfer reactions with accelerated radioactive ion beams in inverse kinematics.
- a novel array of ΔE-E telescopes with thin ($\sim$ 40 μm) ΔE detectors for unambiguous charge (Z) and mass (A) determinations for outgoing beam-like particles following breakup and nucleon transfer reactions that has been developed for use with TIGRESS by collaborators from CSIC Madrid in Spain and the Colorado School of Mines (CSM) in the United States.
- an array of CsI and PIN diodes detectors optimized for light charged particle (proton and alpha) detection in fusion-evaporation reactions that was funded by an NSERC RTI-1 grant and has been developed by the Simon Fraser University (SFU) members of the collaboration.
- the TIGRESS Integrated Plunger (TIP) for picosecond nuclear excited state lifetime measurements funded by a separate NSERC RTI-1 grant and also developed by the SFU members of the collaboration.
- the Spectrometer for Internal Conversion Electrons (SPICE) comprised of a rare earth permanent magnetic lens that guides internal conversion electrons around a photon shield to a

120-segment 6 mm thick Si(Li) detector for in-beam conversion electron measurements with TIGRESS that was funded by a $312k award from CFI and the Ontario Ministry of Research and Innovation (MRI) in 2011.

Finally, TIGRESS can also be coupled with the 70-element DESCANT neutron detector array discussed in section 3.2.2.5 for $\gamma - n$ coincidence measurements.

A new detector development, a TIGRESS silicon tracking array, is foreseen in the future to optimize one-neutron-transfer experiments in nuclei around ^{132}Sn together with the TIGRESS array. The conceptual design includes a multi-layer silicon tracking array combined with a low-pressure ion chamber in front of the gas target, which is ideal to identify isobaric contaminants of the incoming beam. The basic method is to reconstruct the excitation energies, spins and spectroscopic factors of nuclear states from the detected recoiling protons. This development using state-of-the-art detector technologies has the potential to greatly increase the sensitivity of measurements that would then enable studies of the most exotic beams produced by the ARIEL facility.

DESCANT (TRIUMF) Guelph

DESCANT is a $2.0M project that was funded by CFI, the Ontario MRI, and TRIUMF. It couples with both the TIGRESS and GRIFFIN γ-ray spectrometers, replacing 4 of the 16 HPGe clover detectors with a close-packed array of 70 liquid scintillator neutron detectors that cover a 1.08π solid angle. When coupled with TIGRESS, DESCANT detects neutrons following fusion-evaporation and other reactions involving accelerated beams from the ISAC-II superconducting linear accelerator, while in conjunction with GRIFFIN, DESCANT provides a $\beta - \gamma - n$ coincidence detection capability for β-delayed neutron emission studies.

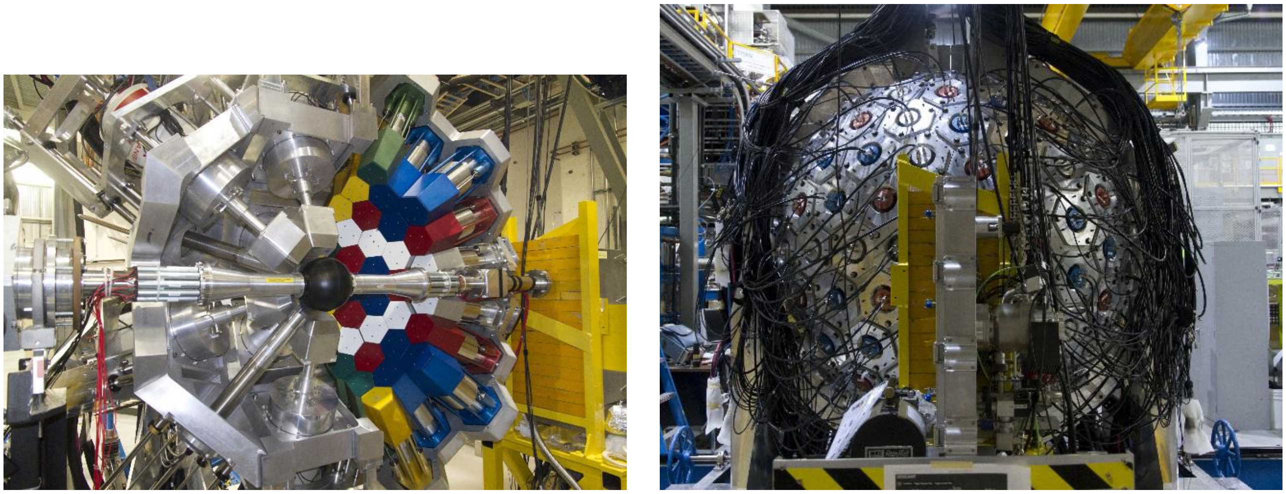


Figure 3.16: DESCANT coupled with the GRIFFIN γ-ray spectrometer. Left: One hemisphere of each of DESCANT and GRIFFIN. Right: A downstream view of the full DESCANT array.

The 70 individual detector elements of DESCANT, which are shown coupled with GRIFFIN in Fig. 3.16, each contain approximately 2 litres of deuterated benzene. It has the advantage over traditional hydrogen-based scintillator materials that the neutron-deuteron scattering cross section is highly anisotropic, resulting in a peak-like structure in the pulse height spectrum. Furthermore, the scattering cross section possesses a minimum at 90 degrees, thus minimizing neutron multiple scattering into adjacent detectors - a problem that often plagues arrays of neutron detectors. With pulse-shape discrimination for separating neutron and γ-ray interactions in the detector, DESCANT represents a powerful tool for nuclear structure and nuclear reaction investigations at both ISAC-I and ISAC-II. First experiments with 8 DESCANT detectors were performed in the autumn of 2014 and the full 70-element DESCANT will begin scientific operation in 2015. With the development of the ARIEL facility and its projected production of high-intensity neutron-rich beams, it is anticipated that DESCANT will play a major role in the research programs with both TIGRESS and GRIFFIN.

IRIS (TRIUMF) Guelph, McMaster, Saint Mary's, SFU; Japan

The ISAC Reaction Induced Spectroscopy station, IRIS, is a facility for studying direct reactions by charged particle spectroscopy using the reaccelerated beams of rare isotopes with energies from 5-12 A MeV provided by the ISAC-II facility at TRIUMF. Construction of the facility was funded by CFI and was developed in partnership with Japan by a Canada-wide collaboration involving Saint Mary's University, University of Guelph, Simon Fraser University, McMaster University and TRIUMF. This collaboration pioneered techniques in developing thin solid hydrogen and deuterium targets (see Fig. 3.17) to boost the reaction yield, thereby allowing reaction studies of very neutron-rich nuclei possible, since they can only be produced with rather small intensity. Such a target is also necessary to eliminate backgrounds arising from the carbon content of polyethylene foils that are typically used elsewhere. A low-pressure ionization chamber is another unique feature of the facility that makes it possible to identify beam contaminants before reaction with the target. Arrays of segmented silicon strip detectors register the reaction products. These powerful, innovative features make IRIS a major world-class facility in Canada.

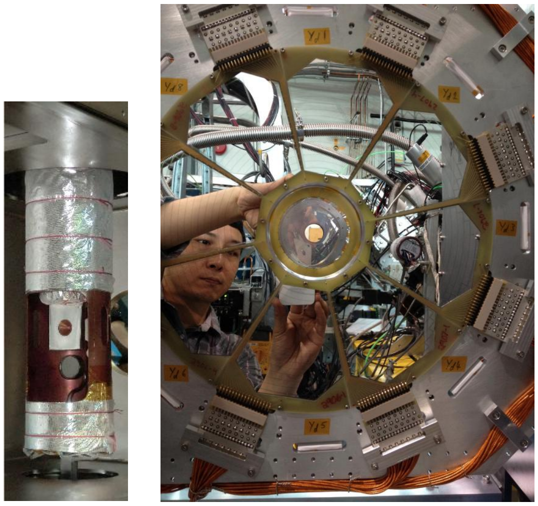


Figure 3.17: The IRIS facility at TRIUMF-ISAC-II. Left: The thin solid hydrogen or deuterium target. Right: One of the highly-segmented silicon detectors of IRIS.

The first scientific program of IRIS will focus on certain key issues where the IRIS facility and ISAC can lead Canada to play a pioneering role internationally in the research of unstable rare isotope science. The study of pairing correlation in neutron halos and skins with two-nucleon transfer reaction is one of the major interests with IRIS. A strong program is planned for understanding the evolution of shell structure through the study of one-neutron transfer reactions in neutron-rich regions, since the appearance of exotic structures and shell structure are closely related. Neutron halos and skins give rise to new modes of excitation, in particular soft dipole resonances that are expected to be neutron-unbound resonances and necessarily require charged particle spectroscopy for their detection. The detection of charged particles is the fundamental requirement to study nucleon transfer reactions.

EMMA and focal plane detectors (TRIUMF) Guelph, McGill, McMaster, SFU, St. Mary's
The Electro-Magnetic Mass Analyser EMMA is a versatile recoil mass spectrometer currently under construction for ISAC-II at TRIUMF. Its large angular acceptance (20 msr) and energy acceptance (±20%) facilitate high recoil detection efficiency without compromising mass resolving power. As such it will be used in a variety of nuclear structure and astrophysics measurements of fusion evaporation and transfer reactions to identify the heavy recoils and isolate them for subsequent decay studies. EMMA has been designed to operate in conjunction with TIGRESS as shown in Fig. 3.18; it is estimated that approximately half of all TIGRESS experiments will require EMMA for coincident recoil detection.

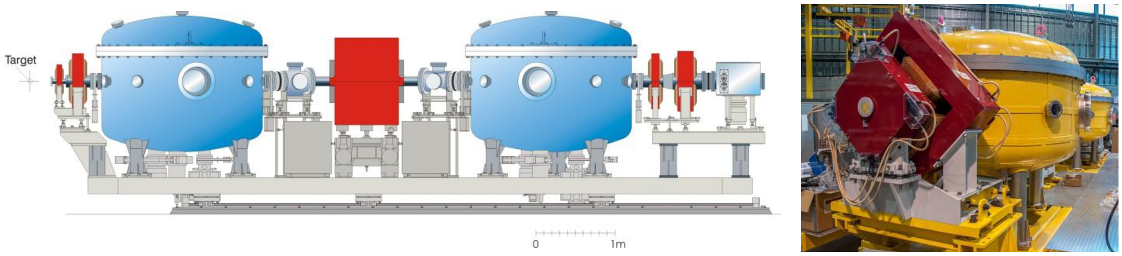


Figure 3.18: The future EMMA spectrometer being installed at TRIUMF-ISAC-II.

EMMA-trap is a new project, which is considering to seek funding from CFI in the 2015/16 period. It will couple a radioactive-beam retardation system (a buffer-gas RF carpet cell) to an ion-guide and trapping experiment. This would provide unique access to high-precision mass measurements of exotic, short-lived radioactive species produced by the fragmentation, knock-out or transfer reactions of a radioactive beam provided at 3-16 A MeV by the ISAC-II facility and separated from the beam by the EMMA mass analyzer.

International collaborations and Canadian-driven programs in offshore laboratories

Canadian Penning Trap (CPT) at Argonne National Laboratory (Argonne) Manitoba, McGill; USA
Canadian physicists from Manitoba and McGill take a lead role in the use and operation of the Canadian Penning Trap (CPT) mass spectrometer at the ATLAS facility of the Argonne National Laboratory. They are joined by collaborators from Argonne, Northwestern University, Berkeley, and Notre Dame University. The CPT has been used for the measurement of super-allowed β decay Q-values for CKM matrix unitarity tests, double-β decay Q-values and atomic masses and Q-values that determine the rates and paths of the astrophysical r- and rp- processes. The isotopes are produced in fusion evaporation reactions or in the fission of ^{252}Cf and are captured, in-flight, in a precision Penning trap. This allows the study of a diverse range of short-lived nuclides independent

of their volatility or chemical properties. These studies are complementary because the TITAN facility at ISAC and the CPT at the CARIBU facility at ANL employ different radioactive ion beam production techniques so different elements are available at each facility.

In the next 1 to 2 year period, it is planned to move the CPT mass spectrometer to a new location at ATLAS where accelerated, high-energy, high intensity beams from the upgraded ATLAS facility will be available. This will allow an extension of mass measurements among neutron-rich nuclei to regions heavier than those directly available through fission. A new gas catcher and a MR-TOF mass spectrometer are under construction at ANL for this measurement program. At the new location, there will be unique opportunities to push measurements towards the N=126 neutron-rich region which is critical for understanding the final abundance peak in the astrophysical r-process.

PREX and CREX (JLab) Manitoba; Croatia, Italy, Slovenia, Ukraine, USA

The PREX II and CREX experiments which will run in Hall A of JLab will make model-independent measurements of the neutron skin of ^{208}Pb and ^{48}Ca, respectively, by measuring the parity-violating asymmetry in elastic electron-nucleus scattering. The Pb Radius Experiment (PREX II) proposes to measure the neutron radius of lead to a precision of 1%, and the CREX experiment proposes to make a 0.9% measurement of the neutron radius of ^{48}Ca. These experiments will provide the best measurement of the neutron radius of nuclei, serving as a fundamental test of state-of-the-art nuclear structure models. The impact on nuclear astrophysics is discussed further in Sec. 3.3.2.3.

Reactions with relativistic beams at the GSI Helmholtz Center for Heavy Ion Research, Germany (GSI) Saint Mary's; China, Germany, Japan, Slovakia, Spain

The rare isotope beams produced via projectile fragmentation at in-flight facilities such as GSI-FAIR (Germany), RIBF-RIKEN (Japan) and NSCL/FRIB (USA) have complementary capabilities for reaction studies compared to the reaction spectroscopy program at TRIUMF with low-energy beams such as described for the IRIS facility. The highest energy beams of $\approx 1A$ GeV are available at GSI, Germany that are ideally suited for measurements of nuclear radii and also for studying nucleon knockout reactions. Use of this facility by Canadian researchers to determine the neutron-skin thickness of exotic isotopes is described further in section 3.3.2.3.

Radioactive Ion Beam Factory (RIBF), RIKEN, Japan Radioactive ion beam production by in-flight fragmentation complements the ISOL production method at ISAC, and Canadian researchers complement their ISOL-based research at TRIUMF with experiments at the RIKEN laboratory in Japan. Current, and future, experiments at RIKEN with participation and/or leadership from Canadian researchers include:

- studies of both extremely neutron-rich and proton-rich nuclei with the EURICA γ-ray spectrometer,
- the "Beta-delayed neutrons at RIKEN" (BRIKEN) project (see Sec 3.3.2.2), comprised of the worlds' largest assembly of ^{3}He-filled proportional counters for the measurement of β-delayed neutron emission branching ratios and half-lives for very neutron-rich isotopes, which will begin operation in 2016,

- study of shell structures and nucleon distributions using the BigRIPS and zero-degree spectrometers at RIKEN,
- in-beam X-ray spectroscopy of super-heavy elements at RIKEN as a new technique to tag the production of super-heavy elements, for which first test experiments are being performed at RIKEN in 2015, and
- the study of fission barrier heights in neutron-rich nuclei, which directly influence fission recycling in the r-process.

Stable beam experiments at offshore institutions Canadian researchers perform experiments at stable beam accelerator facilities around the world. For example, a strong program at the Maier-Leibnitz Laboratorium, located in Garching Germany, using the Q3D magnetic spectrometer to perform transfer and inelastic scattering reactions directly complements both the superallowed Fermi β-decay program described in section 3.4.2.4 and the studies of nuclear collectivity at ISAC, including investigation of Hg isotopes to assist in the construction of models for the ^{199}Hg Schiff moment involved in EDM limits on new CP-odd interactions beyond the Standard Model.

A long standing collaboration with the University of Kentucky involves inelastic neutron scattering experiments to measure lifetimes of highly non-yrast states, and was also recently used to perform tests of the DESCANT neutron detectors. Experiments recently performed in γ-ray spectroscopy following light-ion reactions at the University of Jyväskylä in Finland, have formed a collaboration with the group at the University of Warsaw to perform Coulomb excitation experiments with stable beams, and the Australian National University to measure electric monopole transition strengths in nuclei. These activities further strengthen international collaborations and complement and reinforce the research programs performed at TRIUMF-ISAC.

International involvement in ISAC Another aspect of the international involvement of the ISAC and Canadian nuclear structure community in the world-wide effort should not be overlooked; this is the presence of foreign researchers and students driving science programs at TRIUMF. The vast majority of experiments performed at ISAC include collaborators from foreign institutions, often as the principal investigators of the study. Most of the major pieces of experimental equipment at ISAC have international participation, both financial and specialist expertise, in their construction and in their operation.

As a recent example, the Canadian-led project to design and build the IRIS facility at ISAC has been enabled by significant contributions from Japan. As part of the total capital project cost of the facility, an in-kind contribution of \$200k came from Japan. In addition, key expertise in the development of a world-unique cryogenic, solid hydrogen/deuterium target was provided by collaborators from RCNP and KEK in Japan. These collaborations evolved naturally from the unique expertise and talents of the scientists involved in rare-isotope beams, cryogenic systems and charge-particle detection, as well as a common interest in pursuing an understanding of the physics of light-nuclei such as halo structures.

3.2.3 The next five years and beyond

The highest priority for nuclear physics in Canada in the next 5 years is the full exploitation of high-intensity rare isotope beams for experiments at ISAC that capitalizes on the major investments which have been made in the world-class experimental equipment now operating there. In addition,

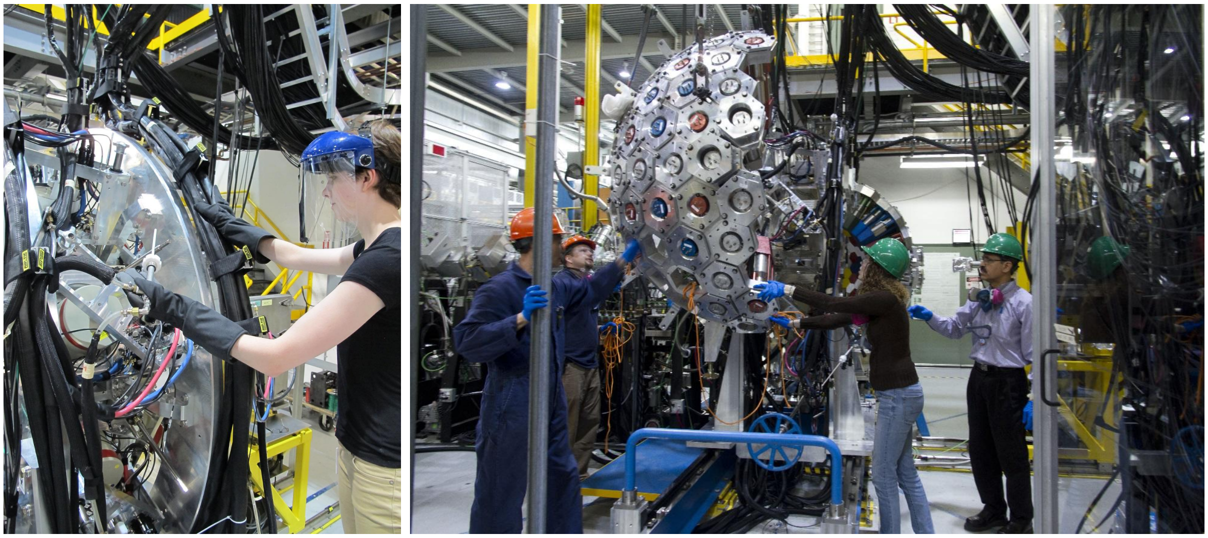


Figure 3.19: Students working with the gamma ray team at ISAC.

preparations must be made over this time period in order to make prompt and full use of the additional rare isotope beams that will be available from the new ARIEL facility. This of course implies the operation of the ISAC facility at its full potential of beam delivery and development for experiments with rare isotope beams. This will be achieved through;

- Immediate replacement of the ISAC target modules with upgraded versions. The present modules have far exceeded their anticipated lifetime but are essential for a reliable beam delivery. Failure of this crucial infrastructure at ISAC puts the success of the entire research program described here in jeopardy.
- Strategic investment in HQP to capitalize on the opportunities available with the world-class experimental equipment now available at ISAC.
- Strengthening and growing the Canadian nuclear theory effort by increased support for HQP which will ensure continued international leadership.
- Continued development of new target materials and techniques to increase the intensity and diversity of rare isotope beams available for experiments at ISAC.
- Timely completion of the ARIEL project to begin concurrent delivery of radioactive beams to multiple experiments at ISAC.

The community will also pursue a broad program of complementary efforts, such as operation of the Canadian Penning Trap at Argonne National Laboratory, that will provide breadth and diversity to nuclear structure research in Canada as well as international visibility and the fostering of collaborations. Detector technology R&D activities will be undertaken in order to maintain a world-leading position in experimental research in the future.

In addition to the completion of the ARIEL-II project and the start of scientific exploitation of the facility during the time covered by the forthcoming Long Range Plan, it is time to consider longer-term possibilities for the future facility development of ARIEL.

One possible future upgrade option for ARIEL/ISAC that will be considered includes the expansion of the ISAC facility, extending the energy range of the ISAC-II SRF linac and feeding beams into a new heavy-ion storage ring where in-ring reaction experiments (with nuclei or electrons) could be performed (see Secs. 4.1.1.4 and 4.3.2). The heavy-ion storage ring should have acceleration capabilities (or at least should be upgradeable to that) for further expansion (e.g. extraction at 150-200 A MeV and secondary fragmentation). The fragmentation of a high-intensity rare isotope beam produced from ARIEL, such as ^{132}Sn, could potentially provide access to very neutron-rich species at beam intensities even beyond the reach of FRIB.

3.2.4 Summary

Nuclear structure research in Canada addresses a range of topics which are of interest in the field today. The research efforts are primarily focussed on experiments performed at the TRIUMF-ISAC facility but are also complemented by experiments performed at other laboratories worldwide. There has been significant Canadian capital investment into the ISAC and ARIEL facilities as well as the individual experimental facilities that have been described in this section. In fact several major pieces of equipment at ISAC have recently been commissioned or have undergone major upgrades. Therefore, in the 2016 to 2026 time period, Canadian researchers are in an excellent position to reap the benefits of these investments by making scientific discoveries in nuclear structure. The timely completion of the ARIEL-II project will be a major enhancement to the rare-isotope beam physics opportunities available at TRIUMF and will ensure Canadian leadership in this exciting research field.

3.3 Nuclear Astrophysics in Canada

3.3.1 Overview

The Canadian Nuclear Astrophysics community is addressing various aspects around the big question "What is the role of nuclei in shaping the evolution of the universe?". The main focus around the creation of elements in stars and the early universe can be broken down further into the following sub-questions:

- What are the different astrophysical origins of the various isotopes from hydrogen up to uranium?
- How does a change of nuclear structure far off stability influence the calculated solar r-process abundance curve?
- What is the role of nuclear reactions in stellar evolution and in the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

The ultimate goal - connecting strongly the nuclear physics and astrophysics efforts - is the theoretical understanding of the quantum many-body problem of the atomic nucleus that would enable a reliably prediction of the properties of *all* nuclei from the proton- to the neutron-dripline. However, since we are still far away from this global understanding, it is essential to study nuclei further and further away from stability with the help of the present and new generation of radioactive beam facilities. These studies are focussed mainly on the neutron-rich side of the valley of stability since the discovery potential there is much higher because we have not yet reached the neutron dripline (S_n=0 MeV) for isotopes beyond oxygen (Z=8). The investigation of exotic nuclei far off stability, e.g. the measurement of excited states, masses, half-lives, particle-emission probabilities etc., helps to constrain theoretical models which are required to extrapolate to more neutron- or proton-rich nuclei which are not (yet) experimentally accessible.

Our knowledge about the creation of isotopes in stars has increased tremendously since about 60 years ago Cameron [Publ. Astron. Soc. of the Pac. 69, 201 (1957)] and Burbidge, Burbidge, Fowler, and Hoyle [Revs. Mod. Phys. 29, 547 (1957)] presented independently their seminal works. Fig. 3.20 summarizes the present-day understanding of the nucleosynthesis of isotopes divided into mass regions. A closer look onto the abundance curve for heavy elements reveals the close connection between nuclear astrophysics and nuclear structure: the abundance maxima are connected to neutron (or proton) shell closures, the rare earth peak at $A{\approx}165$ originates from deformed nuclei far off stability, and the low abundances of ^{138}La and ^{180}Ta^m are due to their odd N, odd Z character.

3.3.1.1 National and international research centers and projects

Astronomy Research Centre (ARC): (University of Victoria) NRC Herzberg, TRIUMF, Victoria

The ARC at the University of Victoria was launched in 2015 and brings together world-renowned researchers with the expertise to answer many basic questions about our universe. Scientists from the University of Victoria, the nearby NRC Herzberg Astronomy and Astrophysics center, and at TRIUMF work closely to form one of the largest concentrations of astrophysics talent in Canada.

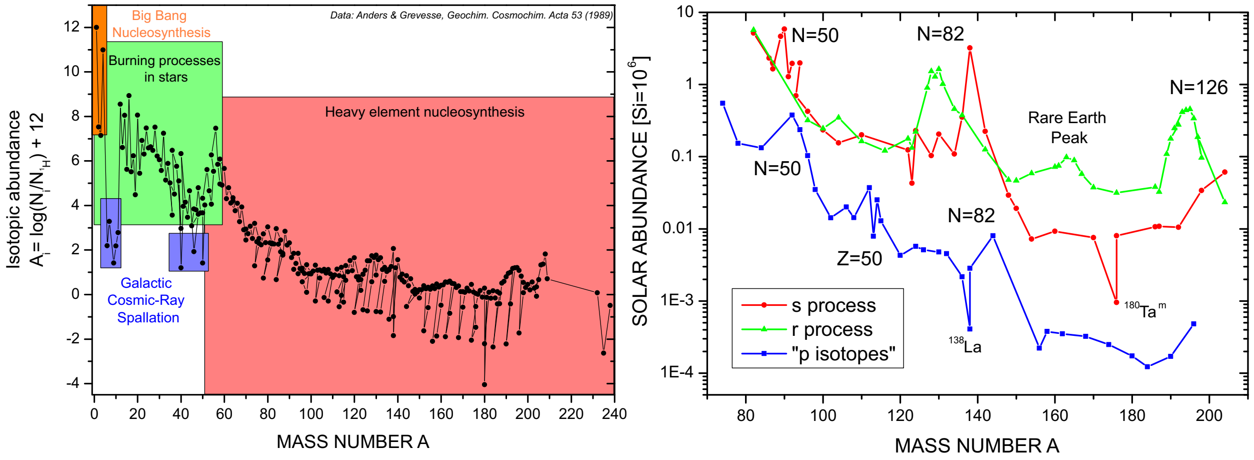


Figure 3.20: Left: Break-down of the observed solar abundances from meteoritic data into the different nucleosynthesis regions. Right: Many features of the heavy element abundance curve are connected to nuclear structure phenomena.

The ARC will centralize research communication, foster synergy and collaborative research, and facilitate teamwork, innovation and leadership. It will also assist in attracting graduate students to more easily identified inter-linked research programs and specific research projects.

Joint Institute for Nuclear Astrophysics - Center for the Evolution of Elements (JINA-CEE): (USA) McGill, TRIUMF, Victoria; Australia, Brasil, China, Germany, USA

The JINA-CEE research is supported by the National Science Foundation in the USA through the Physics Frontier Center Program and addresses fundamental questions at the intersection of astrophysics and nuclear physics. These comprise the evolution and properties of matter in the cosmos, and the origin of the chemical elements.

The focus is on two broad topical areas that constitute the two major activity areas of JINA-CEE and have been propelled to the forefront of the field by new observations, opportunities at new accelerator facilities, and new theoretical developments. The questions they address are:

1. "What are the nuclear reactions and stellar environments producing the isotopes in the first billion years and what are their contributions?" and "How do these nuclear and astrophysical processes interact and evolve as the abundance levels increase?".
2. "What is the equation of state of dense neutron-rich matter?","What are the extreme nuclear and weak processes that shape neutron star observations?", "What are the observational signatures of novel phases of nuclear matter?", and "What are the gravitational wave signatures of merging neutron stars?".

JINA-CEE brings together nuclear experimentalists, nuclear theorists, astronomers, theoretical astrophysicists, and computational physicists in a unique, cross-disciplinary international research network that enables rapid communication and coordination across field boundaries and connects research at new accelerator facilities, observatories.

IAEA Coordinated Research Project about beta-delayed neutron emission (IAEA Vienna) Guelph, McMaster, TRIUMF; China, Croatia, France, India, Japan, Russia, Spain, UK, USA

Canadian researchers have taken a leading role in a recently initiated Coordinated Research Project (CRP) of the International Atomic Energy Agency (IAEA) in Vienna for the "Development of a Reference Database for Beta-Delayed Neutron Emission".

In 2013, the 75th anniversary of the discovery of the nuclear fission process was celebrated. The practical applications of this phenomenon are well known. However, from the point of view of basic physics and technology, many physical properties of this important phenomenon are not understood or measured well. Beta-delayed neutrons (βn) emitted in the fission process, which essentially drive current power and research nuclear reactors, are one such topic. These delayed neutrons play also a crucial role in the late stages of heavy element nucleosynthesis in shaping the r-abundance curve.

A large number of neutron-rich nuclei which will be explored in the future are β-delayed neutron emitters. Yet experimental information on neutron emission probabilities is only available for a third of the identified $\beta 1n$-emitters, and the ratio of measured vs. known βn-emitters gets worse for $\beta 2n$ (<8%), $\beta 3n$ (≈5%), and $\beta 4n$ (≈2%). In addition, present theoretical models show a discrepancy of a factor of $5-10$ for P_{1n} values compared to experimental results (see Fig. 3.29). This uncertainty influences sensitively the amount of neutrons available during late phases of the r process and thus the calculated r-process abundance curves.

The IAEA-CRP started in 2013 and will run until 2017. Its objectives are to coordinate and track progress in new experimental measurements, theoretical model calculations, and empirical systematics of β-delayed neutron emission with the purpose of creating a reference database. This database will contain compiled and evaluated microscopic data ($t_{1/2}$, P_n values, delayed-neutron spectra, access to decay schemes in the ENSDF database for precursors) and recommended macroscopic quantities (total delayed neutron yields, group parameters, decay curves and aggregate delayed neutron spectra for fissile materials of interest).

In 2011-2014 the main Canadian efforts in this project were the evaluation of the half-lives and β-delayed neutron branching ratios of all βn-emitters between $Z= 2-28$ [M. Birch *et al.*, submitted to Nucl. Data Sheets (2015)]. Work on the higher mass region (Z=$29-84$) has already started and is expected to be finished in 2017. These efforts are led by an experienced but already retired evaluator from McMaster University. After the end of this CRP, this invaluable knowledge will be lost since the Canadian nuclear physics community is no longer supporting the evaluation efforts of nuclear physics data at centers like the National Nuclear Data Center (NNDC) in Brookhaven.

3.3.2 The Canadian program

The experimental program of the Canadian groups in nuclear astrophysics can be divided into two main topics:

1. The understanding of the creation of light elements up to the iron peak, and
2. the nucleosynthesis of heavy elements between iron and uranium.

The most important nuclear input parameters during all of these nucleosynthesis phases for the understanding of a reaction flow in a stellar environment are listed in Fig. 3.21. The importance varies depending on the astrophysical conditions, e.g. with temperature, astrophysical scenario, and particle densities.

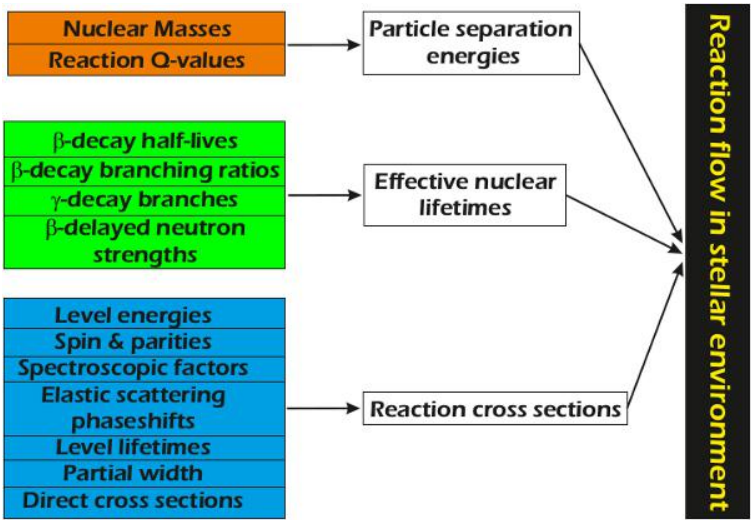


Figure 3.21: Nuclear physics input parameters for the understanding of the reaction flow in a stellar environment.

3.3.2.1 Production of light isotopes up to iron

While Big Bang nucleosynthesis produced only the lightest isotopes up to ^{7}Be and ^{7}Li, heavier isotopes are created in the interiors of stars by fusion processes ("burning phases"), or by Galactic cosmic-ray spallation reactions on abundant species such as ^{56}Fe, ^{16}O, and ^{12}C.

The duration and sequence of the burning phases depend on the mass of the star. Stars with masses between 0.08 and 8 solar masses ($M_\odot$) can only ignite hydrogen and helium burning, whereas massive stars with $> 8\,M_\odot$ additionally proceed through the advanced burning phases up to the production of iron group elements before they end their lives in core collapse supernovae. During the core collapse of a massive star, "explosive" burning phases can be ignited for a few seconds, which reprocess the previously produced material and play an important role for the composition of the later ejected heavier material.

Binary stellar systems contribute also to the nucleosynthesis of light isotopes. Material from a donor star can be transferred to the surface of a more massive stellar object where explosive burning phases can take place. In a "classical nova" this system consists of a white dwarf which accretes material (about $10^{-9}\,M_\odot/$ year) from the hydrogen envelope of a main sequence star or a red giant. This process ignites explosive hydrogen burning reactions on the surface of the white dwarf which is visible as a nova explosion by a luminosity increase of several orders of magnitude and about $10^{-4}\,M_\odot$ of material is ejected. Nova ejecta nebulae (e.g. Nova Cygni 1975, see Fig. 3.22) are enriched in elements such as helium, carbon, nitrogen, oxygen, neon, and magnesium. The contribution to the interstellar medium is only $\frac{1}{50}$ of the contribution of a supernova explosion but they occur much more frequently (about 30 novae/year) and are simpler to model. In this context novae are an ideal testbed for experimental stellar hydrodynamics, and have the potential to be used as a diagnostic tool for the observation of characteristic γ-rays from long-lived radioisotopes or the measurement of isotopes in pre-solar grains.

Another kind of binary system is a X-ray burster which consists of a neutron star which is accreting hydrogen-rich material from a donor star. This material accretes onto the surface of the neutron star, where it forms a dense layer as a result of the extremely high gravitational field. After

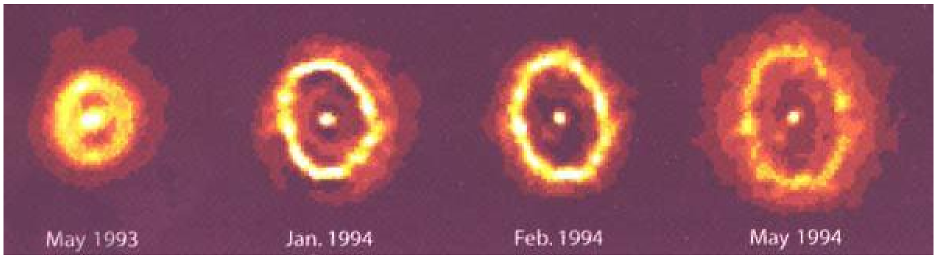


Figure 3.22: Expanding ejecta from the Nova Cygni explosion in 1975. Nova Cygni is a binary system consisting of a white dwarf which accreted material from a red giant. The distance is 6360 light years (source: www.kosmologika.net).

hours of accumulation and gravitational compression, nuclear fusion starts. In some cases the rising temperature leads to a thermonuclear runaway, and explosive stellar nucleosynthesis is ignited via the hot CNO cycle and continues into the "rapid proton-capture (rp) process" (Fig. 3.23). The rp-process proceeds close to the proton-dripline up to $A \approx 110$. Within seconds most of the accreted material is burned, powering a bright X-ray flash that is observable with X-ray telescopes like Chandra, XMM-Newton, or NASA's new NuSTAR space telescope which was launched in June 2012. X-ray bursts recur on timescales ranging from hours to days and carry information about the produced radioactive isotopes in their light curves.

One of NuSTAR's main goals is to characterize star explosions by mapping the radioactive material in a supernova remnant. The NuSTAR map of Cassiopeia A shows the radioactive ^{44}Ti ($t_{1/2}$= 60 y) concentrated in clumps at the remnant's center and points to a possible solution to the mystery of how the star exploded [http://www.jpl.nasa.gov/news/news.php?release=2014-054]. In astrophysical simulations of core collapse supernova explosions, the main shock wave often stalls and the star fails to explode. The latest findings strongly suggest that the material in the exploding star literally sloshes around, which leads to a re-energizing of the stalled shock wave and allows the star to finally blast off its outer layers.

All three scenarios, supernovae, nova explosions and X-ray bursts, require the accurate knowledge of proton- and α-capture reactions on stable and radioactive (neutron-deficient) isotopes within the astrophysically relevant energy range ("Gamow window"). Several detector setups in the ISAC halls at TRIUMF have specialized in the investigation of these reaction rates via different approaches which are summarized below.

The DRAGON facility (TRIUMF) McMaster, Northern British Columbia, Simon Fraser; UK, USA

The DRAGON (Detector of Recoils And Gammas Of Nuclear reactions) setup (Fig. 3.24) at TRIUMF is a recoil separator designed to measure astrophysically important radiative (α and proton) capture rates of stable and radioactive beams. Of particular interest are the reactions which occur in the explosive environments of novae, supernovae and X-ray bursters.

DRAGON is the recoil separator with the highest beam suppression in the world (up to 10^{14}). It was originally designed for reactions with A<30 but has recently expanded its capabilities to the high-mass region up to A≈80. The success of DRAGON lies in its ion-optical design, providing it with superior background rejection qualities which allow measurements to be made with a range of beam intensities. Additionally, its windowless recirculating hydrogen/helium extended gas target

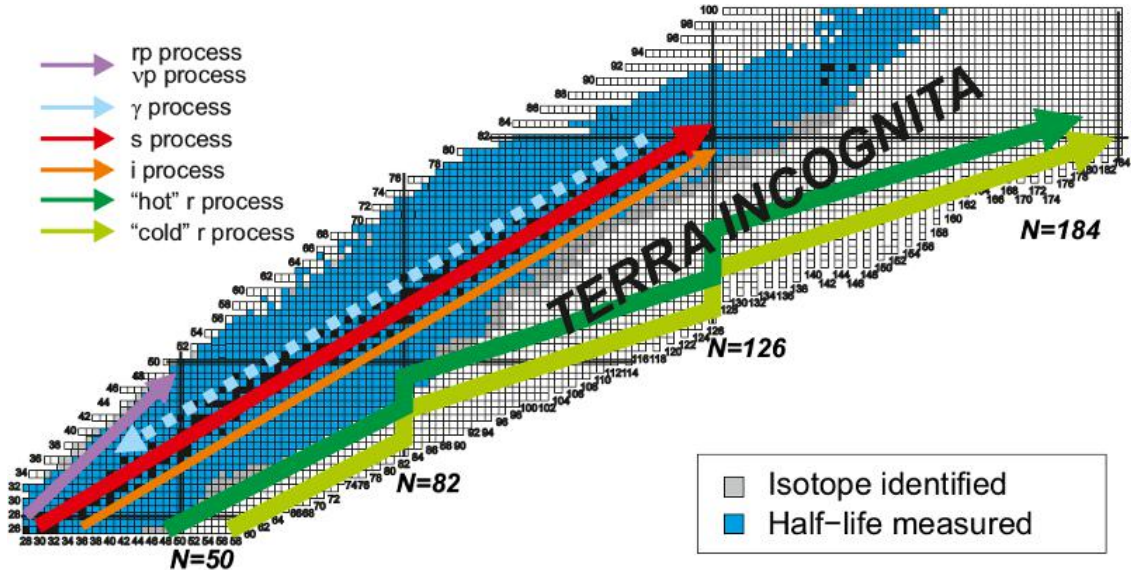


Figure 3.23: Schematic view of the several reaction flows which are responsible for the production of isotopes heavier than iron.

surrounded by a bismuth-germanate (BGO) detector array allows the simultaneous measurement of resonance strength and resonance energy through high-efficiency γ-tagging in coincidence with recoil detection. DRAGON is capable of making measurements of resonant and non-resonant radiative capture reactions, from very light nuclei (e.g. ^{7}Be + p) up to very heavy nuclei (e.g. ^{76}Se + α) for a comprehensive range of astrophysical scenarios.

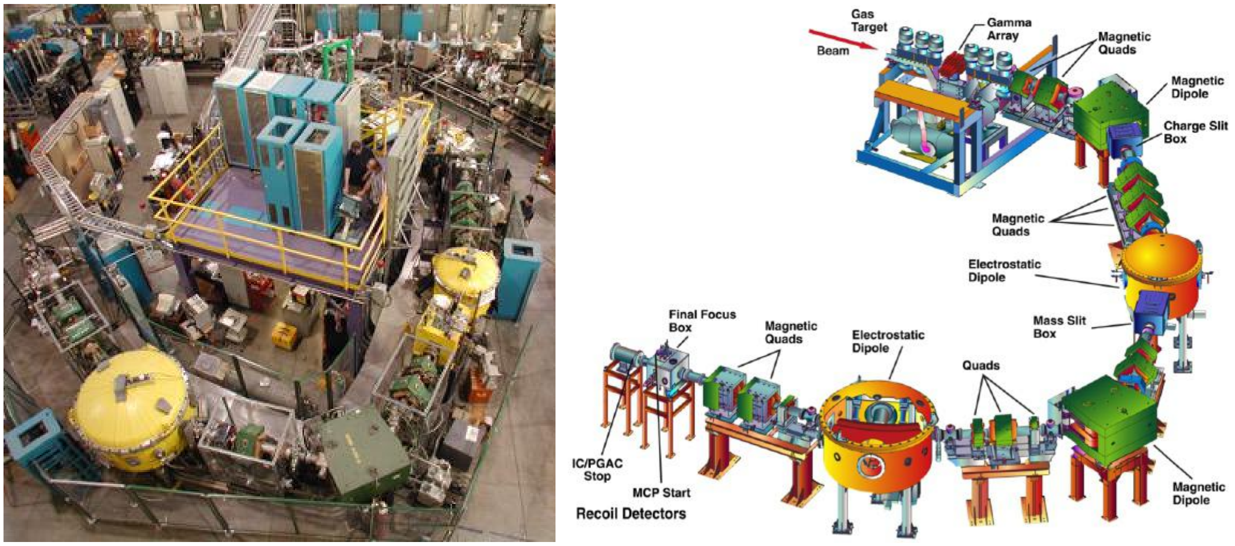


Figure 3.24: The DRAGON recoil separator at TRIUMF.

In the previous LRP period since 2011, the DRAGON facility has extended its radiative capture reaction program with the the first direct measurements of ^{23}Mg$(p,\gamma)^{24}$Al [L. Erikson *et al.*, Phys.

Rev. C81, (2010) 045808] and ^{18}F$(p,\gamma)^{19}$Ne [C. Akers *et al.*, Phys. Rev. Lett. 110, (2013) 262502]. The latter reaction is one of the reactions which destroys ^{18}F, the largest source of 511 keV γ-rays in novae. If rates for both, production and destruction reactions, are well known, observations of the radiation from the annihilation could constrain the physical conditions in novae to improve astrophysical models (e.g. the discrepancy in the ejected mass). Sensitivity studies have shown that a change of a factor 10 in the ^{18}F(p,γ) rate changes the ^{18}F abundance by factor 3.

DRAGON has carried out the first direct measurement of one of the two important resonances in the Gamow window (T= 0.1−0.4 GK) at E_R= 665 keV (E_x= 7.076 MeV). Using a radioactive ^{18}F beam intensity of $\approx 1.7\times10^6$ ions/s, 2 events of the reaction product ^{19}Ne have been detected in 1 week, proving the superior sensitivity of the setup for these small cross sections. The deduced resonance strength was a factor 14 lower than previously assumed. This has lead to the conclusion that this resonance has no significant contribution to the total reaction rate at nova temperatures, but strengthens the importance of the resonance at E_R= 330 keV, which is presently unfortunately out of reach for direct experiments.

So far, seven out of 10 (p,γ) measurements with radioactive beams in inverse kinematics worldwide have been been carried out at DRAGON, including the highest mass RIB radiative capture reaction (^{38}K$(p,\gamma)^{39}$Ca) [G. Christian *et al.*, in preparation for Phys. Rev. Lett. (2015)] for the prediction of Ca abundances in nova ejecta. In the same way, DRAGON has measured the weakest resonance strength ever using the most intense RIB (^{26}Al$^g(p,\gamma)^{27}$Si), and also carried out the first measurement with an isomeric beam (^{26}Al$^m(p,\gamma)^{27}$Si).

In summer 2015, the new scattering chamber SONIK (a project lead by collaborators from the Colorado School of Mines, USA) has been installed. The setup is a modification of DRAGON's windowless gas target to include high-precision scattered particle detection for elastic scattering. This allows high precision, clean, low-energy elastic phase-shift data to be collected - a critical requirement for the input of theoretical models that allow extrapolation of radiative capture cross sections to the lowest energies inaccessible by experiments.

SONIK studies will initially focus on precision measurements of ^{3}He$(\alpha,\alpha)^{3}$He, ^{7}Be$(p,p)^{7}$Be and ^{7}Be$(\alpha,\alpha)^{7}$Be for the astrophysically important ^{3}He$(\alpha,\gamma)^{7}$Be, ^{7}Be$(p,\gamma)^{8}$B and ^{7}Be$(\alpha,\gamma)^{11}$C reactions, work that is intimately tied-in with the *ab-initio* calculations performed by the TRIUMF theory group.

The future DRAGON program will focus on reactions for quiescent and explosive burning in main sequence and giant-branch stars, cataclysmic binary systems (novae, supernovae Ia, X-ray bursters) and core-collapse supernovae, particularly those using radioactive beams. Some of these include: ^{7}Be$(p,\gamma)^{8}$B, ^{11}C$(p,\gamma)^{12}$N, ^{15}O$(\alpha,\gamma)^{19}$Ne, ^{22}Ne$(p,\gamma)^{23}$Na, ^{30}P$(p,\gamma)^{31}$S, ^{34}S$(p,\gamma)^{35}$Cl, ^{19}Ne$(p,\gamma)^{20}$Na, ^{7}Be$(\alpha,\gamma)^{11}$C, and ^{72}Ge$(\alpha,\gamma)^{76}$Se. DRAGON is currently the only recoil separator in the world capable of doing these measurements and is therefore an unique asset to Canada. The nearest competitor, SECAR at FRIB, is still several years away from starting its experimental program.

The total capital investment for the setup of the DRAGON facility up to today is \$3.0M. Planned future improvements to the facility include the upgrade of the current ion optical system to optimize performance for high-mass radiative capture (beyond DRAGONs original design parameter of $A<30$) and a more efficient γ-tagging setup ($LaBr_3$) which will be shared with the EMMA setup, see Sec. 3.3.2.2. This will allow the identification of γ-cascade transitions (and thus vastly improved systematic uncertainties in the measurements) and the separation of close narrow resonances using fast timing. Thus resonance energies can be measured with minimal statistics and in a range of beam contaminant conditions and intensities, expanding the number of reactions accessible for direct measurements.

The TUDA detector (TRIUMF) McMaster, Northern British Columbia, Simon Fraser; UK

The TUDA (TRIUMF-UK Detector Array) charged-particle scattering and reaction detector array is a collaboration with the University of Edinburgh and the University of York. It consists of highly segmented large-solid angle silicon detectors with exceptional energy resolution characteristics and is primarily used for direct charged-particle (α, p) and (p, α) reactions or elastic scattering cross-section measurements with gaseous and solid targets. TUDA is a portable detector which can be installed in both ISAC experimental halls to indirectly constrain reaction rates or to provide important nuclear structure information (e.g. excitation energies, spin and parities) to guide direct measurements. These reactions address problems in massive star nucleosynthesis, thermonuclear and core-collapse supernovae, and classical novae.

TUDA has enabled the extension of ^{18}F$(p, \alpha)^{15}$O reaction studies into the astrophysically-important energy regime. This reaction is one of the most important reactions for novae since it dominates the destruction of the strongest 511 keV emitter ^{18}F [C. Beer *et al.*, Phys. Rev. C83, (2011) 042801(R)]. The TUDA collaboration has also completed a high-profile measurement of the ^{26}Al$^g(d, p)^{27}$Al transfer reaction to indirectly constrain the ^{26}Al$^g(p, \gamma)^{27}$Si reaction [V. Margerin et al., Phys. Rev. Lett. 115, 062701 (2015)]. This measurement has produced data in extremely high quality with an energy resolution comparable to spectrometer measurements in normal kinematics. This technique extends the capabilities of TUDA as a precision device enabling access to previously unreachable nuclei.

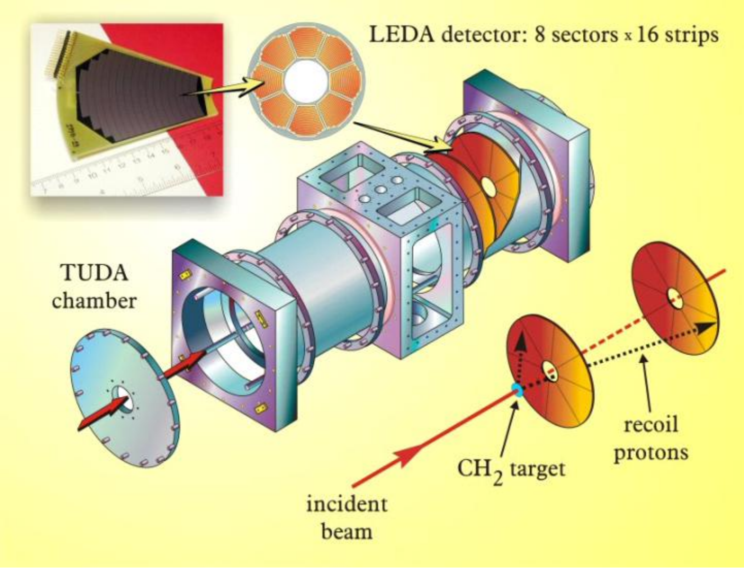


Figure 3.25: Sketch of the TUDA detector at TRIUMF.

The TUDA program in the next years will continue with measurements of the very important ^{18}Ne$(\alpha, p)^{21}$Na and ^{44}Ti$(\alpha, p)^{47}$V reactions for X-ray bursters and core-collapse supernovae, respectively. TUDA will additionally perform resonant elastic scattering measurements with radioactive beams to determine resonance parameters and elucidate nuclear energy level properties in cases of astrophysical interest, using the state of the art AZURE2 R-Matrix code, which is accessible through TRIUMFs collaboration with JINA-CEE (Sec 3.3.1.1). These measurements also will serve to refine *ab-initio* calculations in the light mass region, providing valuable data to be compared with cross sections and phase shifts calculated by the TRIUMF theory group.

SHARC-TIGRESS (TRIUMF) Guelph, SFU, Saint Mary's; France, Spain, UK, USA

The TIGRESS γ-spectroscopy setup (Sec 3.2.2.5) in combination with the SHARC particle detector can also be used for the measurement of astrophysically relevant transfer reactions.

The ^{15}O$(\alpha,\gamma)^{19}$Ne reaction is crucial for the understanding how much material is transferred from the hot CNO cycles during explosive He burning into heavier breakout sequences up to the *rp* process. The strength of this reaction not only regulates the ignition point of an X-ray burst during an outburst but also affects the recurrence rate. While most present nova models claim that the conditions for the breakout are not realised, the start-up of a Type I X-ray burst on the surface of a neutron star depends critically upon this reaction rate. The ^{15}O$(\alpha,\gamma)^{19}$Ne reaction is dominated by a single resonance at E_x= 4.033 MeV in ^{19}Ne.

A direct experimental measurement remains presently hampered by limited production yields, which are 2−5 orders of magnitudes too low for experiments at the DRAGON facility. Past studies have therefore focused mainly on the use of indirect techniques to measure the characteristic nuclear structure features of the ^{19}Ne compound nucleus required to determine resonance parameters for the reaction rate.

The remaining quantity to be determined is the α-decay branching ratio $B_\alpha = \frac{\Gamma_\alpha}{\Gamma}$ that has mostly been estimated from the α-strengths of the mirror states in ^{19}F with large systematic (model dependent) uncertainties inherent to the analysis of α-transfer reactions on ^{15}N. Several attempts have been made in the past to measure the relative α-decay widths directly. While this approach was successful for higher-lying states in ^{19}Ne, it has failed so far for the critical levels near the α-threshold due to the small decay branching. It is planned to access the astrophysically important excited state in ^{19}Ne at 4.03 MeV via the ^{6}Li$(^{15}O,d)^{19}$Ne* transfer reaction with SHARC and TIGRESS. This experiment will help to constrain important X-ray burst parameters like the recurrence rate of bursts which presently vary from several hours to days.

Other nuclear astrophysics activities at TRIUMF-ISAC

Doppler-Shift Lifetime (DSL) station (TRIUMF) Western

The DSL facility measures femtosecond nuclear level lifetimes using the Doppler shift attenuation method, using implanted targets and a variety of populating reactions. It provides critical nuclear structure information to indirectly constrain nuclear reaction cross sections of astrophysical importance. One recent example is the measurement of the lifetime of states in ^{15}O via the ^{3}He$(^{16}O,\alpha)^{15}$O reaction [N. Galinski *et al.*, Phys. Rev. C 90, (2014) 035803].

Implantation of isotopes of astrophysical interest (TRIUMF) Spain, USA

The nuclear astrophysics group has also had success with implantation of long-lived ^{22}Na ($t_{1/2}$= 2.6 y) and ^{26}Al^g ($t_{1/2}$= 717000 y) targets at the ISAC Implantation Station.

The ^{22}Na sample was used in a direct measurement of ^{22}Na$(p,\gamma)^{23}$Mg in normal kinematics, and ^{26}Al^g will be used in spectrometer experiments for astrophysics in Europe and the USA.

Theoretical efforts for light element nucleosynthesis A detailed description of the theoretical program with focus on astrophysical reaction rates can be found in Sec. 3.5.2.9

At TRIUMF, the theory group is developing a unified approach to nuclear structure and reactions, the no-core shell model with continuum (NCSMC), capable of simultaneous description of bound and unbound states from first principles, i.e., from accurate nucleon-nucleon and three-nucleon interactions derived within chiral effective field theory (χEFT).

Future plans for the TRIUMF theory group include calculations of (p, γ), (α, γ) and (n, γ) capture reactions in light nuclei that are relevant for astrophysics. The group will also study the connection between reaction mechanisms of the (n, γ) and (d, p) reactions as the latter is frequently used as a surrogate for the (n, γ) cross section determination in exotic nuclei (see Sec. 3.3.2.2). The ultimate goal for the next five years is to study reactions involving ^{4}He, e.g., ^{8}Be$(\alpha, \gamma)^{12}$C, ^{12}C$(\alpha, \gamma)^{16}$O, as well as the neutron source reaction ^{13}C$(\alpha, n)^{16}$O relevant for the s-process.

3.3.2.2 Production of elements heavier than iron

When Discover Magazine published in 2002 the "11 Greatest Unanswered Questions in Physics", question 3 was *"How were the heavy elements from iron to uranium made?"*. We have a rather good understanding how about 50% of these abundances are produced in a process called the "slow neutron capture (s) process". This reaction path (see Fig. 3.23) runs along the valley of stability through known isotopes.

However, the question is still partially unanswered for about 50% of the heavy abundances which originate from isotopes far off stability in the "rapid neutron capture (r) process" (Fig. 3.27). One major issue of the r process is that we are still lacking a full understanding of the exact astrophysical scenario(s), and thus the astrophysical conditions which lead to the production of these neutron-rich isotopes. One of the most striking features of the solar abundances curve is the connection between isotopes at neutron shell closures (N=50, 82, and 126) with the abundance maxima of the respective processes, and additionally for the r-process abundance curve the connection of the "mini" peaks at $A \approx 100$ and 160 (see Fig. 3.27) with the region of deformed nuclei. This gives a first guidance for the measurement of key isotopes. Up to now most r-process isotopes were investigated at the N=50 and 82 shell closures around doubly-magic ^{78}Ni and ^{132}Sn. The future focus at the present and next-generation of RIB facilities will be the access to more neutron-rich isotopes in the so-called experimental "Terra Incognita" (see Fig. 3.23), beyond A=150 and especially at the third r-process peak around N=126 and around the rare earth peak at $A \approx 160$.

Massive stars with $> 8\ M_\odot$ (Fig. 3.26) play a crucial role in the stellar production of isotopes heavier than iron and the mixing of material into the interstellar medium via core collapse supernova explosions. The final stage of such an explosion can be either a neutron star, or a black hole. The astrophysical sites for the production of r-process nuclei remain heavily debated. The classical description requires high neutron densities of $\gg 10^{20}$ cm^{-3} and moderate temperatures around 1.35 billion Kelvin in order to drive the reaction path from the Fe/Ni seed nuclei deep into the neutron-rich region and up to the fissile actinide nuclei above U and Th within a few seconds.

Despite many improvements in stellar modelling in the past decades, the only conclusion that can currently be drawn is that the solar r-process abundances N_r (Fig. 3.27) — deduced from the measured solar abundances $N_\odot$ minus the calculated s-process abundances N_s — are not created by one single astrophysical scenario but may arise from several independently operating processes.

For many years the favored r-process site was the so-called "neutrino-driven wind scenario" close to the forming neutron star during a core collapse supernova explosion. However, this model requires unrealistically high entropies to reach the heaviest nuclei at the N=126 shell closure, and neutrino captures on neutrons turn the material proton-rich at later times.

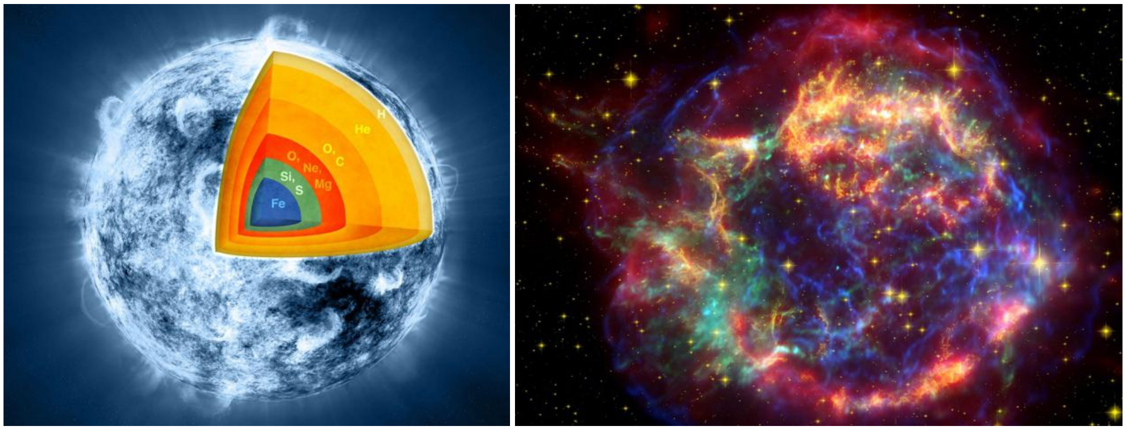


Figure 3.26: Left: Onion-like structure of a massive star before a core collapse supernova (Credit: NASA/CXC/M. Weiss). Right: Chandra image of Cassiopeia A, a supernova remnant from a core collapse supernova that exploded around 335 years ago. The glowing hot debris can be seen via X-rays at various energies (represented by different colors). (Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScl; Infrared: NASA/JPL-Caltech/Steward/O.Krause *et al.*).

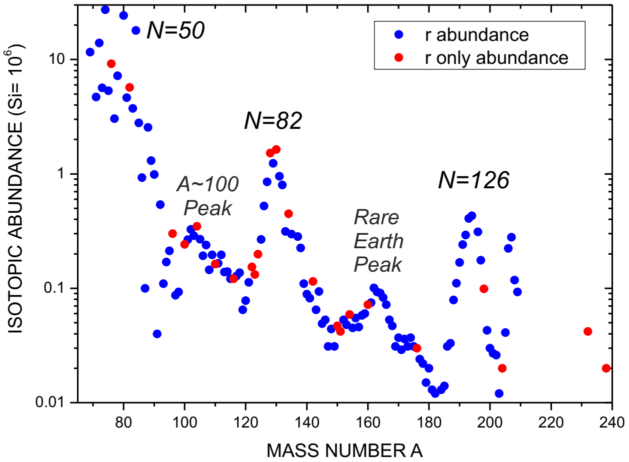


Figure 3.27: The r-process residuals with the distinct abundance peaks at neutron shell closures. The mini-peaks at A≈100 and 160 originate from deformed nuclei. [Data: Anders and Grevesse, Geochim. Cosmochim. Acta 53 (1989)].

A more promising scenario is that of neutron star mergers (see Fig. 3.28). The high neutron densities drive the reaction path close to the neutron dripline up to the region around $A \approx 260$ where fission recycling sets in and produces a very robust r-process abundance pattern for isotopes with $A > 130$. However, the encounter and merger of two neutron stars (or a neutron star and a black hole) cannot account for the r-process abundances observed in very old metal-poor halo stars in our galaxy since this scenario implies a time-delay of several hundred million years compared to core collapse supernovae.

Other presently discussed scenarios include jet-like explosions in magnetically-driven core collapse supernova explosions [e.g. N. Nishimura et al., arxiv 1501.06567v1 (2015)]. In this scenario,

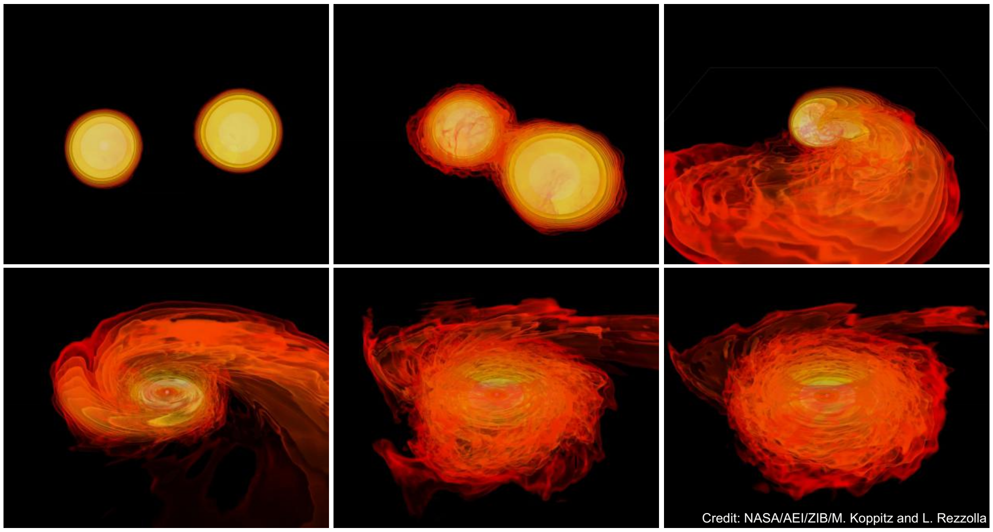


Figure 3.28: Simulation of the merging of two neutron stars. Neutron-rich r-process material can be ejected by the tidal waves.

the explosion is induced by rotation and strong magnetic fields. A "delayed magnetic-jet explosion" could be an explanation for the observed light r-process abundances in old metal-poor stars, while an explosion with strong magnetic fields leads to the production of heavier abundances.

Since the reaction path of the r-process is determined by the temperature, the respective neutron density, and the masses of the participating nuclei (Saha equation), the uncertainties in the astrophysical scenario translate directly into the uncertainty as to which isotopes are "the" r-process isotopes to investigate experimentally. The reaction path of the core-collapse supernova scenario corresponds more or less to the region of the classical ("hot") r-process path (see Fig. 3.23) which can already now be partially accessed by experiments around the $N= 50$ (^{78}Ni) and $N= 82$ (^{132}Sn) regions.

Neutron star mergers (Fig. 3.28) or fast cooling core-collapse supernovae produce a much more neutron-rich environment ("cold" r-process) which drives the reaction path about 10 mass units further neutron rich (Fig. 3.23), even beyond the neutron dripline. This region is not accessible with present techniques and will stay a Terra Incognita for several decades until new accelerators and reaction mechanism are developed which are able to produce these extremely neutron-rich and short-lived ($t_{1/2} < 10$ ms) isotopes close to the neutron dripline.

However, both scenarios have in common that during the "freeze-out phase" when the temperature or the neutron density drops, the material decays back to stability via long β-decay chains and produces the observed stable r-process abundances in Fig. 3.27. For this reason, the decay properties of all isotopes between the respective r-process path and the line of stability are required for r-process calculations. The most important nuclear physics input parameter are masses (which define the reaction path), half-lives and β-delayed neutron-branching ratios (which define the shape of the r-process abundance distribution). In addition, the shell evolution towards the neutron dripline is also an important information for benchmarking theoretical models, which are required for a further extrapolation to the many experimentally unexplored isotopes in the r-process reaction path.

One of the nuclear physics parameters whose importance will increase steadily in the upcoming years is the β-delayed neutron (βn) emission probability because it is the dominant decay process for more neutron-rich isotopes. These neutrons can be emitted whenever the neutron separation energy S_n becomes smaller than the reaction Q-value. They are called "delayed" since they are emitted with the half-life of the progenitor, in contrast to the prompt neutrons emitted directly after the fission process. The range of half-lives for βn emitters is from ≈ 80 s for the longest-lived down to a few ms for the most neutron-rich isotopes identified so far.

The detection of the β-delayed neutrons is almost as old as the discovery of the fission mechanism, but only since the 70's have significant measurements of the neutron emission probabilities (P_n values) from fission products (and also for low-mass nuclei in the non-fission region) been performed. During the last decade there has been a renewed interest in the experimental and theoretical study of neutron-rich nuclei far off the stability thanks to RIB facilities and the astrophysical motivation from the r process.

As outlined before in Sec. 3.3.1.1, there is a large discrepancy between the presently accessible and already measured isotopes, as well as in the accuracy of these measurements. One major problem for nuclear astrophysics is the present discrepancy between the experimental and theoretical predictions which is a factor of $5-10$ for the β1n-emission probability (P_{1n}), as shown in Fig. 3.29. This discrepancy might be even higher when extrapolating to the isotopes in the r-process paths, and influences the availability of neutrons at the later freeze-out phase. This has a direct impact on the calculated r-abundance curves, especially on the smoothing of the even-odd-staggering and the position of the abundance peaks, e.g. the rare-earth peak at $A\approx160$ (Fig. 3.27).

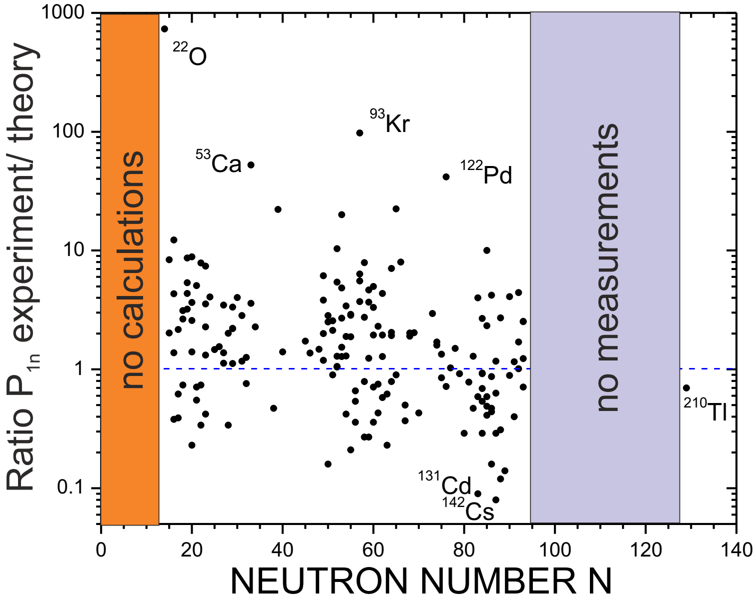


Figure 3.29: Ratio of measured P_{1n} values (taken from the Evaluated Nuclear Structure Data File (ENSDF) database) and theoretically predicted values from [P. Möller *et al.*, Phys. Rev. C67, (2003) 055802]. The average discrepancy is a factor of $5-10$.

Spectroscopy of very neutron-rich isotopes with GRIFFIN and DESCANT (TRIUMF)
Guelph, SFU; USA

The recently commissioned GRIFFIN spectrometer (see Sec. 3.2.2.5) in conjunction with the DESCANT neutron detector (see Sec. 3.2.2.5) is an ideally suited setup for the investigation of short-lived βn-emitters. These two powerful detectors were commissioned together in 2015 and are important tools for high-precision γ- and neutron-spectroscopy of astrophysically important nuclei. They aim at measurements of exotic isotopes down to 0.01 pps production rates.

One example for the superior sensitivity of the GRIFFIN setup combined with the production of clean laser-ionized beams from the Ion-Guide Laser Ion Source (IG-LIS) at ISAC are the recent $^{128-132}$Cd β-decay measurements with production yields down to 0.5 pps. The statistics achieved in this experiment were higher than a recent measurement performed at the presently leading RIB facility at RIKEN Nishina Center using the EURICA setup and could solve several discrepancies to older decay data from ISOLDE. Of special interest was the re-measurement of the half-live of the N=82 r-process waiting-point isotope ^{130}Cd. The confirmation of the 20% shorter value will have some impact in r-process simulations since ^{130}Cd is the isotope responsible for the 2nd abundance peak (see Fig. 3.27).

The upcoming experimental program with GRIFFIN and DESCANT will focus on targeted high-precision measurements of βn-emission probabilities and neutron spectra for nuclear astrophysics and reactor studies, in close conjunction with the recommendations of the IAEA-CRP (Sec. 3.3.1.1).

Measurements of β-delayed neutron emitters with BRIKEN (RIKEN) Guelph, TRIUMF; Japan, Russia, Spain, UK, USA

The "Beta-delayed neutron measurements at RIKEN" (BRIKEN) project is a large international collaboration which aims at merging up to 180 ^{3}He-filled neutron proportional counters from various experimental setups (Germany, Japan, Russia, Spain, and the USA) into one world-leading high-efficiency setup. In combination with AIDA (Advanced Implantation Detector Array) from UK collaborators this setup will run from 2016 on for several years at the BigRIPS separator at RIKEN Nishina Center in Japan. This facility is presently at the forefront for the discovery of new isotopes, especially on the neutron-rich side. Two proposals have been accepted so far (one with a researcher from TRIUMF as spokesperson), and the $\beta 1/2/3n$-emission probabilities for about 60 isotopes between ^{76}Co and ^{152}Ba will be measured, many of them for the first time. In comparison to the βn-program at TRIUMF with GRIFFIN and DESCANT, the focus of the BRIKEN experiments is the discovery and first-time measurements of isotopes (which cannot be produced elsewhere). These isotopes have very low production rates, and due to the restricted beamtime at RIKEN the measurement of large mass ranges ($\approx$30 isotopes per experiment) restricts the precision which will be achieved for the most neutron-rich species.

Two subdetectors of the BRIKEN setup, the 3Hen setup from the USA and the BELEN detector from a Spanish-German collaboration, have expressed their interest to bring their detectors to TRIUMF for measurements after the BRIKEN campaign.

Mass measurements of neutron-rich isotopes with traps TITAN (Sec. 3.2.2.5) and the Canadian Penning Trap (CPT, Sec. 3.2.2.5) are devices which are also ideally suited for high-precision measurements of very neutron-rich isotopes.

In recent years, the CPT has operated on the low-energy beam line of the new Californium Radioactive Ion Beam Upgrade (CARIBU) facility at Argonne National Lab to measure the masses of neutron-rich nuclei produced in the fission of ^{252}Cf. CARIBU utilizes a large scale gas stopping technique to provide a source of very neutron-rich nuclides, produced in the fission of a 1.7 Ci source of ^{252}Cf. Approximately 100 nuclides have been studied so far. The shorter half-lives of more exotic isotopes require a faster measurement process. The installation of a position-sensitive ion-detector will dramatically reduce the time needed for the measurement of the cyclotron frequency of the ions. A multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS), used to separate the contaminating ions that are injected into the Penning trap, is nearing completion. The new system will reduce the measurement time required from hundreds of ms to hundreds of μs, pushing the measurements closer to the r-process path and providing access to a wide range of nuclei which are presently not available elsewhere.

The measurement program of TITAN at TRIUMF (see Sec. 3.2.2.5) has been focussed in the previous years on the lighter mass region and addressed mainly nuclear structure questions. Presently, the facility is extending its capabilities (e.g. with the installation of a multi-reflection time-of-flight setup, MR-TOF) to precision mass measurements of astrophysically important neutron-rich isotopes.

The i-process and the new EMMA recoil separator (TRIUMF) Guelph, McMaster, Saint Mary's, SFU

The nuclear structure program of EMMA is discussed in Sec. 3.2.2.5. Recent astrophysical models and observations imply that a third neutron capture process with intermediate neutron densities (10^{14}-10^{16} n/cm^3, compared to 10^7-10^{10} n/cm^3 in the s-process and $>10^{20}$ n/cm^3 in the r-process), the so-called "i-process", may also exist. The reaction path of this intermediate neutron capture process is $2-5$ mass units away from stability in the neutron-rich region and requires the same nuclear input parameters as for the s-process, namely neutron capture rates, decay half-lives, and a good knowledge of isomers and excited states. Direct neutron capture measurements on short-lived nuclei with half-lives less than 0.5 years are, however, not yet possible as the radioactive targets cannot be produced in μg quantities (corresponding to roughly 10^{16} atoms) and are hard to handle.

A method to overcome this lack of direct neutron capture data is through (d,p) neutron-transfer reactions with accelerated radioactive beams using the ElectroMagnetic Mass Analyser EMMA (see Fig. 3.18) which is currently under construction at TRIUMF. EMMA will be used in a variety of nuclear structure and astrophysics measurements of fusion evaporation and transfer reactions to identify the heavy recoils and isolate them for subsequent decay studies. In particular, (d,p) reactions such as $^{87}\text{Kr}(d,p)^{88}\text{Kr}$ will be studied to infer the (n,γ) reaction cross section indirectly. In addition, EMMA will be able to perform radiative capture reaction out of reach of the DRAGON facility.

EMMA has been designed to operate in conjunction with TIGRESS/SHARC and DESCANT, and it is estimated that approximately half of all TIGRESS experiments will require EMMA for coincident recoil detection. It is currently in the final stages of construction and is anticipated to be operational in 2016.

Other key reactions for studying the i-process, such as $^{135}\text{I}(d,p)$ will become possible with the high-intensity neutron-rich beams that will be produced by ARIEL in a few years.

Heavy neutron-rich program at IRIS (TRIUMF) Guelph, McMaster, Saint Mary's, SFU; Japan

The light nuclear structure program of the IRIS facility is described in Sec. 3.2.2.5. The astrophysical focus for the upcoming years is described in Sec. 3.3.3.1.

3.3.2.3 Neutron star physics and the equation of state

With a radius of roughly 12 km and densities of up to twice the nuclear matter density, neutron stars are the smallest and densest stars in the universe. The behavior of matter under such extreme conditions is governed by quantum chromodynamics (QCD). Neutron stars probe the low temperature and high density region of the nuclear phase diagram and offer a unique opportunity to test and explore the richness of QCD in a regime that is beyond the reach of terrestrial experiments. While laboratory experiments at colliders like RHIC and the LHC explore the high-temperature/ low-density regime, astrophysical studies probe the opposite, low-temperature/high-density regime.

One of the central questions in the astrophysics of neutron stars is the relation between the pressure and the density, the so-called equation of state (EoS, $P \propto \rho^{\alpha}$). In contrast to the EoS of white dwarfs which can be described with special relativity, the neutron star EoS needs to consider increased effects from general relativity. When translated into a mass-radius relation (see Fig. 3.30) neutron star mass measurements can help constraining these predictions and make better predictions of the behaviour of neutron star matter. A harder EoS ($\alpha \geq 5/3$) produces a larger radius for the same mass and thus a higher maximum neutron star mass.

The conservative Tolman-Oppenheimer-Volkoff (TOV) limit (analogous to the Chandrasekhar limit for white dwarf stars) lies in the range $1.5 - 3.0 M_{\odot}$. The uncertainty in the value reflects the fact that the EoS for extremely dense matter is not well constrained. In a neutron star below the TOV limit, the weight of the star is balanced and the collapse prevented by the strong force and the quantum degeneracy pressure of neutrons. If the mass of the neutron star is above the limit, the star will collapse to some denser form like a black hole or via a quark-hadron phase transition into a quark star. Since the latter is still hypothetical, it is assumed that neutron stars above the TOV limit collapse directly into a black hole.

PREX and CREX: Measuring the neutron skin thickness (JLab) Manitoba; Croatia, Italy, Slovenia, Ukraine, USA

The proton distribution in nuclei can be deduced from electron scattering experiments. However, extracting the neutron distribution was up to now only possible via scattering of hadrons, such as protons, antiprotons, and pions. Interpreting this data depends critically on the chosen theoretical strong nuclear force model.

The theory of the nucleus contains terms that depend on the difference of the proton distribution and the neutron distribution. There is a strong correlation between the radius of the neutron distribution R_n and the EoS of neutron matter. Therefore, measuring the neutron radius has important implications for nuclear astrophysics, particularly for the structure of neutron stars, and will help to understand how many neutrons can be added to a heavy nuclei until it reaches the neutron dripline. This will improve our understanding of which nuclei are involved in the heavy element nucleosynthesis via the r-process.

The neutron skin of lead correlates strongly with the EoS of neutron matter, but *ab-initio* calculations for this nucleus are not yet feasible, and another method, such as density functional theory (DFT) must be used. The Lead Radius Experiment (PREx) and the Calcium Radius Experiment (CREx) at JLab will make model-independent measurements of the neutron skins of ^{208}Pb and ^{48}Ca. In these experiments, stable targets of doubly-magic ^{208}Pb ($N/Z = 1.54$) and ^{48}Ca ($N/Z = 1.4$) are bombarded with 1.06 GeV or 2.2 GeV polarized electrons. Measurement of the parity-violating asymmetry, A_{PV}, in electron scattering from heavy nuclei provides a model-independent probe of neutron densities that is free from most strong-interaction uncertainties. Combining known nuclear charge densities, which have been determined accurately with electron scattering, with a measurement of the weak charge density allows to determine the neutron skin of a heavy nucleus. A_{PV} is sensitive to the radius of the neutron distribution R_n. The Z boson that mediates the weak neutral interaction couples mainly to neutrons and provides a clean measurement of the RMS radius of the neutron distribution in the nucleus and is a fundamental test of nuclear structure theory.

The first run of PREX-I performed the first measurement of A_{PV} by the elastic scattering of polarized electrons from ^{208}Pb and demonstrated the ability to achieve the stated systematic uncertainty. It measured A_{PV}=0.656± 0.060(stat)± 0.014(syst) ppm [S. Abrahamyan *et al.*, Phys. Rev. Lett. 108, (2012) 112502]. This result corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm, the first electroweak observation of the neutron skin expected in a heavy, neutron-rich nucleus.

The second run of the PREX experiment (PREX-II) will provide the originally anticipated statistical uncertainty of ±0.06 fm. In addition, the Calcium Radius Experiment (CREX) will measure the neutron skin of ^{48}Ca with an uncertainty of ±0.03 fm. Both experiments will run after the 12 GeV upgrade at JLab as early as spring 2017.

Ab-initio calculations for calcium are possible, thus a measurement of the neutron skin of calcium in CREX will allow to bridge the regions where *ab-initio* calculations and DFT overlap in the chart of the nuclides. A measurement on calcium will provide an important test of nuclear models which provide information about three-nucleon interactions.

Nuclear radii measurements at the GSI Helmholtz Center for Heavy Ion Research, Germany (GSI) Saint Mary's; China, Germany, Japan, Slovakia, Spain

The measurements of matter radii of nuclei approaching the neutron-drip line paved the leading step to the the discovery of the nuclear halo and neutron skin. The density derivative of the symmetry energy L has a linear relationship to the neutron skin thickness. The sensitivity of constraining L is higher for larger values of the skin thickness, and hence neutron-rich nuclei form the ideal investigation grounds. Such measurements are complementary to and extend beyond the reach of neutron skin determination from parity violation measurements for ^{208}Pb and ^{48}Ca at Jefferson Lab described in Secs. 3.2.2.5 and 3.3.2.3.

It has now been well established that the matter radius can be derived from the measurement of interaction cross sections. The advantage of this technique in comparison to proton elastic scattering is the feasibility to extend the measurement to extremely neutron rich nuclei with only $0.1-1$ particles per second production yield. It is for such highly neutron-proton asymmetric rare isotopes that unexpected phenomena appear and the neutron surface becomes appreciably extended.

The new technique of extracting proton radii from charge changing cross section is emerging as a useful direction to determine the skin thickness of extremely neutron-rich nuclei. The proton radii in neutron halos are also necessary to determine the correlation between the core and the halo neutrons. In addition, the proton and matter radii provide a knowledge on the average correlation of the two halo neutrons and the core nucleus.

The Canadian-led program at the in-flight fragmentation facility at GSI has already made a successful start with such measurements on light neutron-rich nuclei extending from Li to Mg isotopes, and recently in B and Be isotopes [A. Estrade *et al*, Phys. Rev. Lett. 113, 132501 (2014)]. The proton radii for boron isotopes show a rather monotonic increase with mass number while those for ^{12}Be and ^{14}Be were very similar. A very thick neutron surface was found as a result in ^{17}B (≈0.5 fm) and in ^{14}Be (≈0.7 fm). The results combined with known matter radii outlines

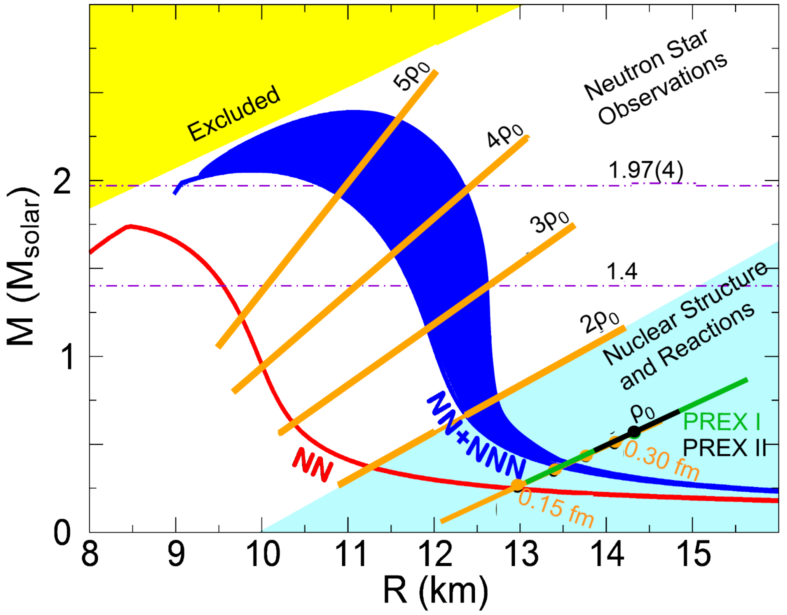


Figure 3.30: Plot of theoretical correlation between the mass of a neutron star (in units of solar mass) vs. the radius of a neutron star (in km). The red curve shows the correlation including nucleon-nucleon (NN) forces with the width of the line indicating the theoretical uncertainty. The blue curve shows the correlation including three-nucleon forces (NN+NNN). The orange lines indicate the corresponding density of neutron matter in terms of nuclear densities (ρ_0). The PREX-I measurement and its uncertainty has been added in green on the line corresponding to 1 ρ_0. The PREX-II measurement (black data point) will help to normalize the theory at nuclear density while CREX will improve the uncertainty on the width of the curve including three nucleon forces. (Modified picture from S. Gandolfi *et al.*, http://arxiv.org/abs/1501.05675)

the three-body halo correlation. The difference in rms radius between the halo neutrons in ^{14}Be is rather large while their center of mass is located closer to the ^{12}Be core than in the case of ^{17}B. This gives a cigar-like configuration for ^{14}Be.

The interaction cross section measurements on neutron-rich oxygen and magnesium isotopes demonstrated a faster increase in radius than the $A^{1/3}$ dependence showing the development of neutron skin. The measurement for ^{23}O resolved a long-standing anomaly showing that it is not a one-neutron halo but rather a nucleus with a neutron skin. An increase in radius observed for ^{35}Mg signaled the gradual development of halo structure. In recent times groups in Japan have confirmed a one-neutron halo in ^{37}Mg.

3.3.3 The next five years and beyond

3.3.3.1 The next five years (2016-2021)

The Canadian astrophysics program in the next five years will greatly profit from further developments towards the completion of the ARIEL facility at TRIUMF and the 12 GeV upgrade of JLab in the USA, as well as the ongoing research programs at in-flight fragmentation facilities like GSI in Germany, RIBF in Japan, and NSCL at Michigan State University.

Due to the close connection, all comments and recommendations given in the Nuclear Structure section (Sec. 3.2.3) also hold for the astrophysics program. The near-future astrophysics program at the ISAC facilities is also crucially dependent on the reliability of the presently used target modules for production of high-intensity radioactive beams.

In parallel to the ARIEL project, there are discussions at TRIUMF among the astrophysics group and the accelerator division to provide novel methods for the production of high intensity medium-to-long lived radioactive beams for astrophysical studies. The program (Versatile Advanced Spallation Target, VAST) aims to develop production targets deviating from the standard solid, high-temperature, 'steady-state' ISOL target approach currently employed at ISAC. It proposes targets containing lithium salts or other suitable materials with higher vapour pressures, to induce spallation on light nuclei such as fluorine or chlorine. These produce compounds which can diffuse out of the graphite container with high efficiency. The goal is to provide high-intensity radioactive beams with high astrophysical priority such as ^{15}O, ^{18,19}Ne, ^{30}P, ^{44}Ti that have not been produced from standard ISAC production targets.

Once ARIEL is completed, the use of photo-fission (in comparison to proton spallation) will allow to produce much intenser and cleaner neutron-rich beams. The new proton-beamline (BL4N) will allow additional and highly needed independent beam developments. The most striking advantage for all experiments after completion of the ARIEL construction is the availability of up to three parallel beams. This will allow longer beamtimes for the study of small astrophysical cross sections.

In the following the near-future astrophysics program of several setups is given in alphabetical order.

BRIKEN at RIKEN The offshore experimental nuclear astrophysics program will focus on the measurement of yet unknown βn-emitters at RIKEN in Japan with the BRIKEN setup starting in 2016. Two proposals have been accepted so far, and the $\beta 1/2/3n$-emission probabilities for about 60 isotopes between ^{76}Co and ^{152}Ba will be measured, many of them for the first time.

The discovery potential of this campaign is large and will set the bar for future measurements at other in-flight fragmentation facilities like FRIB and FAIR, and will give valuable information for future high-precision measurements and theoretical predictions of more neutron-rich isotopes. Parts of the collaboration have expressed interest to bring their detectors to TRIUMF after the completion of the BRIKEN campaign in 2018/19.

CPT at Argonne In the next 1 to 2 year period, it is planned to move the CPT mass spectrometer to a new location where accelerated, high-energy, high intensity beams from the upgraded ATLAS facility will be available. This will allow an extension of mass measurements to regions heavier than those directly available through fission. A new gas catcher and MR-TOF-MS are under construction at ANL for this program. At the new location, there will be unique opportunities to push measurements towards the N=126 neutron-rich region.

DRAGON at TRIUMF The upgrade of the DRAGON facility will enable the performance for high-mass radiative captures, beyond the original design parameter of $A < 30$. This upgrade would enable the extension of the physics program to capture measurements on radioactive isotopes for the heavy element nucleosynthesis in the γ and rp-process. In addition, the more efficient LaBr$_3$ γ-tagging setup will allow the identification of γ-cascade transitions and the separation of close narrow resonances using fast timing. Resonance energies can then be measured with minimal statistics (thus in shorter beamtimes), expanding the number of reactions accessible for direct measurements.

EMMA at TRIUMF The completion and commissioning of EMMA in 2016 is an important milestone to enable unique measurement capabilities which are presently not possible elsewhere. EMMA will allow not only the nuclear structure but also the astrophysics group to extend their programs. One important astrophysical topic will be the measurement of (d,p) reactions to provide input for (n,γ) cross section measurements of radioactive, neutron-rich species for the i-, s-, and r-process nucleosynthesis.

GRIFFIN and DESCANT at TRIUMF The experimental program of GRIFFIN and DESCANT will be complementary to the program at in-flight fragmentation facilities like BRIKEN at RIBF. The goal will be to perform high-statistics and high accuracy γ- and neutron-spectroscopy. Several proposals have already been accepted, and others will follow soon. The IAEA-CRP (Sec. 3.3.1.1) has provided several recommendations for high-priority measurements which will be tackled with this setup in the next years.

IRIS at TRIUMF The future program at IRIS will be to to reach out to the neutron-rich Sn isotopes beyond N=82 with beams from the ARIEL facility. These (d,p) neutron transfer reactions on key isotopes in the neutron-rich nuclear landscape spanning between the N=50 and 82 conventional closed shell regions will also provide an indirect measure of the (n,γ) capture reaction rate in addition to providing the shell structure information.

Nuclear radii measurements at GSI In the coming years, this program will be extended to measurements in the region of medium heavy and heavy isotopes.

PREX-II and CREX at JLab The second run of the PREX experiment (PREX-II) will provide the originally anticipated statistical uncertainty of ±0.06 fm. The Calcium Radius Experiment (CREX) will measure the neutron skin of ^{48}Ca with an uncertainty of ±0.03 fm. This measurement will provide an important test of nuclear models which provide information about three-nucleon interactions. Both experiments will run after the 12 GeV upgrade at JLab as early as spring 2017.

SHARC-TIGRESS at TRIUMF An experiment led by researchers from the University of York/UK aims to access the astrophysically important excited state in ^{19}Ne at 4.03 MeV via the ^{6}Li$(^{15}O,d)^{19}$Ne* transfer reaction using SHARC and TIGRESS at ISAC. The α-transfer spectroscopic factor will be measured, from which the α-width can be extracted. The reaction rate for this resonance can then be determined indirectly since the energy and spin are known. This experiment will help to constrain important X-ray burst parameters like the recurrence rate of bursts which presently vary from several hours to days.

TITAN at TRIUMF TITAN will be extending its capabilities with the installation of a multi-reflection time-of-flight setup (MR-TOF). This device will allow to use cleaner beams to push the range for precision mass measurements further away from stability to isotopes with lower production rates and will add a valuable component to the astrophysics program in Canada.

3.3.3.2 Long-range vision (2022-2026)

Apart from ARIEL at TRIUMF, several next-generation radioactive beam facilities which are presently under construction are expected to provide first beams in the years between 2022-2026. The Canadian Nuclear Astrophysics community will also explore the complementarity of these experimental programs to the domestic program at TRIUMF.

Possible extensions of the ISAC facility at TRIUMF As described in Sec. 3.2.3, the long-range vision is the full exploitation of the new beam opportunities which are enabled by the ARIEL project.

Beyond this, an extension of the ISAC facility with a heavy-ion storage ring and an in-flight fragmentation facility is an exciting opportunity to go beyond the reach of present fragmentation facilities and enable the production and investigation of even more neutron-rich beams (see Sec 4.1.1.4).

Beyond CREX at JLab Possible future measurements of PREX-II and CREX include parity-violating electron scattering from other isotopes such as doubly-magic ^{40}Ca or an isotope of Sn (Z=50). A measurement at higher energies and smaller angles where cross section is larger would shorten the required beamtime. This could fully map out where the neutrons and protons are in a nucleus.

3.3.4 Summary

The Canadian nuclear astrophysics program has evolved enormously over the last years and stepped out of the shadow of its counterpart in the USA. It has grown to a full program covering several topics around the the big question *"What is the role of nuclei in shaping the evolution of the universe?"*. The extent of this chapter and the diversity of the experiments described here displays the popularity of this interdisciplinary field. Especially in view of the possibilities enabled by the new RIB facilities which are under construction world-wide, it is expected that this field will further grow.

The Canadian astrophysics community wants to highlight the opportunity that these new experimental capabilities bring with them. It is timely to bridge the present gap in the heavy-element nucleosynthesis program between the experimental program, and the Canadian theoretical astrophysics community. The hire of a stellar modeller focussing on this topic would be a big opportunity to maintain and enhance the Canadian leadership in this field.

3.4 Fundamental Symmetries

3.4.1 Overview of the major scientific questions and current efforts addressing them

Low energy tests of fundamental symmetries in nuclei and atoms have traditionally played an important role in the search for 'new physics' beyond the Standard Model. The field is more active than ever, particularly in Canada, where it is represented by the working group "Fundamental Symmetries" within the Canadian Institute of Nuclear Physics (CINP). The study of symmetries in subatomic physics is of key importance for two reasons. On one hand, the fundamental forces and conservation laws of nature are intimately linked to corresponding symmetries; the investigation of those symmetries and their violations gives unique insights. In addition, from a practical point of view, symmetries can be exploited to single out vanishingly small signatures of new physics in the presence of much larger 'conventional' interactions, giving low-energy experiments a physics reach to energy scales orders of magnitude higher, and keeping them competitive with direct searches conducted at colliders. As an example, at the Z-resonance, the neutral current weak interaction dominates as real Z bosons are readily observed in $e^+ - e^-$ collisions; in an ordinary atom with binding energies on the order of electron volts, the Z-boson exchange amplitude between electrons and quarks is 12 or more orders of magnitude suppressed relative to the prevalent electromagnetic photon exchange, yet with help of the violation of the parity symmetry in the Z-exchange, this amplitude has been measured to 0.3%, providing an important test of electroweak physics.

Our current understanding of the fundamental interactions and symmetries is reflected in the Standard Model; constructed 40 years ago, it is essentially still in agreement with experimental findings. It is a quantum field theory founded on the assumptions of Lorentz symmetry and invariance under the combined transformation of charge (C), parity (P), and time reversal (T), or CPT. Since the 1950s and 60s we know that C, P, CP, and T are violated separately. However, the Standard Model contains an uncomfortably large number of free parameters, and while the P and CP symmetry violations have been successfully incorporated, the Standard Model cannot explain their origin. In addition, no link exists between the Standard Model and gravity.

Theories such as quantum gravity and string theory are pursued intensely as a unifying approach valid up to the Planck scale. While they yield the Standard Model and general relativity in the low-energy regime, they frequently assume Lorentz and CPT violation. High precision, low-energy fundamental symmetry-type experiments in nuclei and atoms can probe for very faint remnants of these symmetry violations occurring at energies far beyond the current frontier of direct searches.

In Canada, there is currently a strong community of researchers working on fundamental symmetry tests. The work covers many of the hot topics and also has a remarkable breadth in the experimental approaches, from electron scattering experiments at the 10 GeV level to beta decay in laser traps using atoms at neV temperatures, a span of 19 orders of magnitude in energy!

3.4.2 The Canadian program in fundamental symmetries

3.4.2.1 Time reversal and CP violation: Permanent electric dipole moments and related searches

The CP violation in the Standard Model is 10 orders of magnitude smaller than needed to generate the observed baryon asymmetry of the universe in the method outlined by Sakharov. The observation of a non-vanishing permanent electric dipole moment (EDM) in an atom, nucleus, or the neutron and proton would directly violate time reversal symmetry (and also CP, assuming CPT symmetry holds), independent of any need for radiative corrections or theoretical interpretation. EDM searches are among the hottest topics for physics beyond the Standard Model world-wide. Several Canadian groups are active in this field at the confluence of atomic, nuclear, and particle physics. Experiments are under development or in the planning stage at TRIUMF, exploiting a unique mix of capabilities: The cyclotron is the backbone of the high-density, ultra-cold neutron facility, enabling a competitive neutron EDM search. It is the driver for the actinium targets at ISAC, which produce record quantities of radioactive, heavy elements such as Rn, Fr, and Ra which are of particular interest for fundamental symmetries studies due to the large enhancement of T/CP (and also P) violating interactions. The RnEDM experiment critically depends on the existence of advanced gamma ray detector arrays. A possible search for an electron EDM in Fr and T-violating triple-correlation measurements in the radiative beta decay of ^{38m}K harness the world-leading radioactive neutral atom trap infrastructure at ISAC. ARIEL rounds out the synergies by enabling long, dedicated campaigns with actinide target beams.

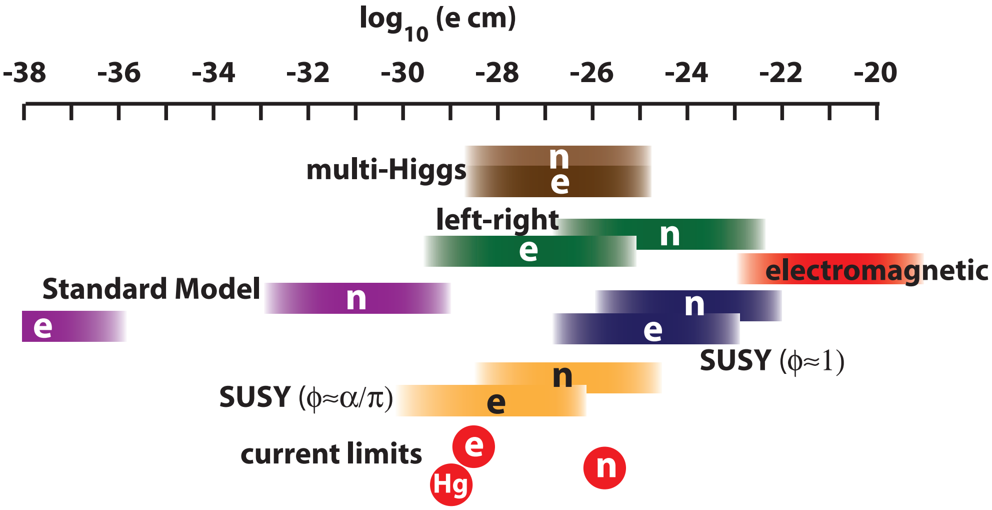


Figure 3.31: Experimental limits on permanent electric dipole moments (red circles) and predicted ranges for various theories. Based on Pendlebury and Hinds [Nucl. Meth. Instr. A 440, 471 (2000)], experimental values from Chupp and Ramsey-Musolf [Phys. Rev. C 91, 035502 (2015)].

The nEDM experiment (TRIUMF) Manitoba, SFU, UBC, UNBC, Winnipeg; Japan.

The neutron electric dipole moment (nEDM) experiment at TRIUMF aims to make the world's best measurement. An observation of a non-zero nEDM would be interpreted as a discovery of CP-violation, sources of which are permitted within and beyond the Standard Model (SM). The previous best measurement of the nEDM, performed by a group from Sussex, RAL (UK), and ILL (France), placed an upper limit that is 2.9×10^{-26} e·cm. Theories of physics beyond the Standard Model, which aim to explain the matter-antimatter asymmetry of the universe, predict values of the nEDM as large as 10^{-26} e·cm. This means that almost any new measurement of the nEDM has the potential to make an immediate discovery.

The limiting factor historically in nEDM experiments has been the number of available neutrons.

The experiment at TRIUMF leverages a new source of ultra-cold neutrons (UCN) being constructed at TRIUMF by a Japanese-Canadian collaboration, with first operation foreseen in late 2016. The UCN source uses a unique technology: it is the only spallation-driven, superfluid helium UCN source in the world. Using this technology is projected to result in world-record UCN densities.

Phase 1 of the project (prior to 2018) will build on and improve an existing nEDM prototype apparatus constructed at RCNP, Osaka. In Phase 2 (after 2018), a new nEDM experimental apparatus and upgrades to the UCN source are envisioned. These upgrades will allow the experiment to improve upon the currently best result by a factor of thirty.

The key features of the Phase 2 experiment are: 1. a room temperature apparatus allowing rapid optimization bulding on technology used in the previous best experiment, 2. a dual species (Xe/Hg) comagnetometer, the first of its kind, allowing cancellation of the dominant systematic effect envisioned to limit future experiments arising from magnetic gradients, 3. state-of-the-art magnetic shielding, field generation, and measurement technologies.

Though the nEDM experiment will be the focus of the facility for the next five years, it is planned to create a facility capable of supporting two or more UCN experiments at the same time. The other top science priority experiments in this field are measurements of the neutron lifetime and of quantized energy levels of UCN confined by gravity.

The construction of the UCN source and the Phase 1 nEDM experiment was supported by a \$11.12M CFI investment. With a future, similarly sized CFI request, early in the 2022-2026 period, the nEDM experiment will be completed and development will begin on further upgrades and on other UCN physics experiments. Looking beyond, full exploitation of a world-class international user facility welcoming further experiments is foreseen.

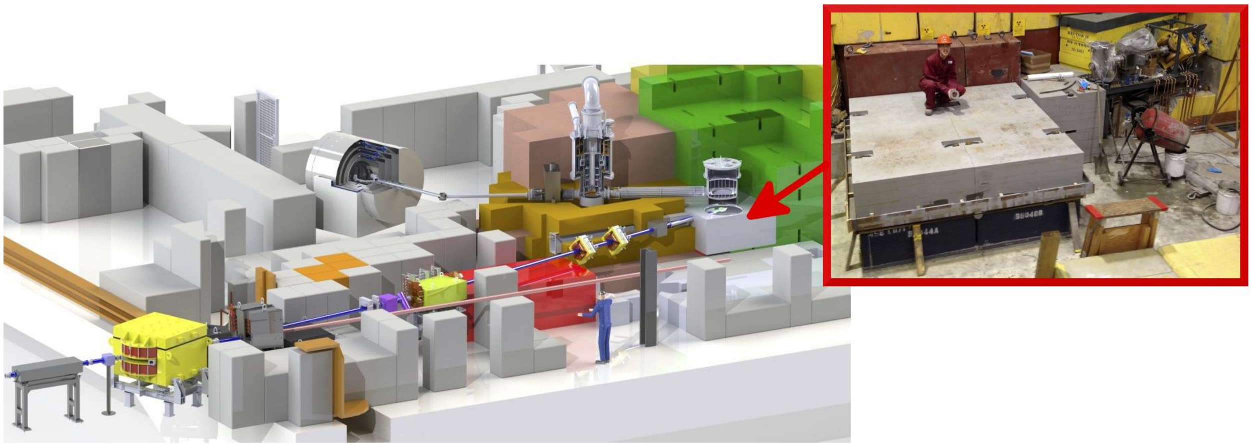


Figure 3.32: Schematic diagram of the UCN facility under construction at TRIUMF. (Inset) Final installation of the base of the radiological shielding pyramid (gray).

Radon EDM search at ISAC (TRIUMF) Guelph, SFU; USA.

Nuclear octupole deformation is predicted to dramatically enhance (up to 1000-fold) the observed atomic EDMs. Among the potential candidates are neutron-rich isotopes of radon such as ^{221,223}Rn, intense beams of which can be produced from the actinide production targets at ISAC. The predicted EDM enhancements in these nuclei depend sensitively on their nuclear structure, which is virtually unknown. As a first part of a RnEDM campaign, dedicated nuclear structure measurements with GRIFFIN for these Rn isotopes in the coming 5 years will be essential to establish their octupole deformation properties and suitability for a high-precision RnEDM search at ISAC. Should a candidate isotope be identified with an octupole-deformation-induced doublet to the ground state with opposite parity (which can induce a T-odd Schiff moment of the nucleus through mixing with the ground state induced by a CP-violating interaction) at sufficiently low excitation energy, a full-scale Rn EDM search program would commence at ISAC in the 2022-2026 period.

Search for an electron EDM in laser-trapped francium at ISAC (TRIUMF); USA.

An intrinsic electron EDM is strongly enhanced in heavy atoms, among which Fr stands out as an element which is easy to capture and cool in a neutral atom trap. A LBNL/SLAC collaboration has published a proof-of-principle experiment for measuring the electron EDM in Cs in a cold-atom fountain [Amini *et al.*, Phys Rev A75, 063416 (2007)], and a detailed proposal for a Fr experiment (where the signal is $\approx 10\times$ bigger compared to Cs, while much larger tensor polarizabilities suppress systematic errors by an additional factor of 25), has been established. A recent analysis of EDM sensitivies by Chupp and Ramsey-Musolf [Phys. Rev. C 91, 035502 (2015)] concludes that a Fr EDM fountain experiment achieving similar sensitivity to the great recent advances in ThO by the ACME collaboration would allow complementary separation of the electron EDM from semileptonic TRV interactions. The statistical signal achieved by the Fr fountain can be similar to ACME, as the long integration times possible in a fountain balance the high internal electric fields of ThO. After initial off-line preparations, such an experiment could be staged by 2021 at an ISAC beamline.

T-violation in radiative beta decay of laser-trapped ^{38m}K at the TRINAT facility (TRIUMF) USA, Israel.

A time-reversal-violating correlation not involving the nuclear spin, but instead a triple product of the three independent momenta of the β, ν, and γ from radiative beta decay, has been proposed by Gardner and He [Phys Rev D 87, 116012 (2013)] as a neutron decay experiment, also pointing out that a higher-Z decay such as in ^{38m}K is about two orders of magnitude more sensitive. The sensitivity is to MeV-scale physics like a hidden QCD-like sector, evading collider experiments by hiding in jet backgrounds. The new physics Lagrangian involves the direct production of the gamma with the leptons, an unusual source of physics relatively insensitive to present constraints from spin-dependent correlations like the D coefficient and EDMs. A number of high-energy experiments have looked for such physics at higher scales, including K radiative decay, along with recent 4-body final state decays at LHCb and BABAR.

By adding 10-100 keV γ detectors, the existing TRINAT laser trapping setup can be adapted to carry out triple momentum correlation measurements. The predicted asymmetries are only constrained to be less than about 10%, and a near-term demonstrator experiment aims for 1% sensitivity, also serving as a feasibility study for a more ambitious campaign within the 10-year time frame.

3.4.2.2 Neutral current weak interactions

The violation of parity symmetry provides for an extremely sensitive means to study the neutral current weak interaction, which is generally masked by the dominating electromagnetic processes. P-violating physics beyond the Standard Model at the TeV scale can be observed in low-energy experiments, keeping this field competitive in the LHC era. For example, when new states are discovered at the LHC, it will be important to know their couplings to the first generation of particles. Electrons and muons can be distinguished in the LHC detectors, but up/down quark jets cannot be separated from jets of other generations. Low-energy experiments are in a unique position to assist with this question. There are three types of such low-energy weak neutral current measurements with complementary sensitivity. Electron-electron scattering (MOLLER) is measuring the electron's weak charge, electron-proton scattering (Qweak) determines the proton's weak charge and atomic parity violation (FrPNC) is predominantly sensitive to the neutron's weak charge. Different types of 'new physics' contribute differently to each of them. For example, the atomic weak charge is relatively insensitive to one-loop order corrections from all SUSY particles; Moeller scattering is purely leptonic and has no sensitivity to leptoquarks. The Canadian community has had a long, prominent involvement in parity-violating scattering experiments and is playing a major role in the Qweak and MOLLER collaborations at Jefferson Lab. In addition, the recently formed FrPNC collaboration aims to measure atomic parity violation in laser-trapped francium at TRIUMF, ultimately hoping to improve on the Cs result. The Canadian involvement in the PREX/CREX experiments (see section 3.3.2.3) nicely ties into this work by providing critical input to the francium experiment via the determination of nuclear neutron radii.

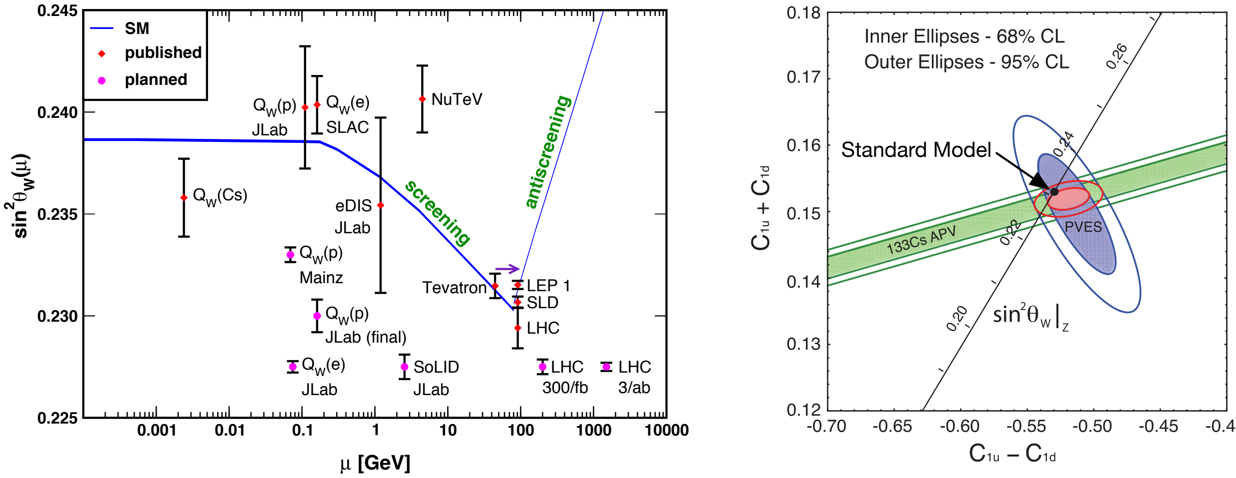


Figure 3.33: Left: Measurements of the weak neutral current strength as a function of momentum transfer; θ_W is the Weinberg angle. Note that the experiments have very different sensitivity to 'new physics'; figure courtesy J. Erler. Planned experiments are placed arbitrarily along the vertical axis. Right: Constraints on weak electron-quark couplings from electron scattering and atomic parity violation measurements in Cs [Androic *et al.*, Phys. Rev. Lett. 111, 141803 (2013)], showing their complementarity.

Theoretical work on one-loop and two-loop electroweak radiative corrections of critical importance to the parity experiments is carried out by groups at Memorial/Acadia and Manitoba (see theory section).

The weak charge of the proton: The Qweak experiment at JLab (JLab) Manitoba, TRIUMF, UNBC, Winnipeg; Armenia, Australia, Croatia, France, USA.

The Qweak experiment at Jefferson Laboratory was developed to measure the proton's weak charge, via parity-violating electron-proton scattering, to high precision. The experiment featured an intense (180 μA) longitudinally polarized electron beam at 1.16 GeV incident on the world's highest power (2500 W) liquid hydrogen target. Scattered electrons at very small momentum transfer were selected by a triple collimation system and guided by a large room-temperature toroidal spectrometer to an 8-fold symmetric ring of synthetic quartz Cerenkov detectors read out in current mode. A novel diamond microstrip detector was incorporated in a new Compton polarimeter upstream of the Qweak apparatus, which enabled the beam polarization to be monitored continuously to unprecedented precision. Design and construction of the apparatus took place from 2003 - 2010, immediately followed by an intense period of data taking from 2010 - 2012 in Jefferson Lab's Hall C. Early results, based on the Qweak commissioning run (4% of the total data), were published in 2013 (see Figure 3.34). A detailed analysis of the full Qweak data set is nearing completion, with final results expected to be released by 2016. They are expected to have an uncertainty approximately the size of the plotting symbols in Figure 3.34.

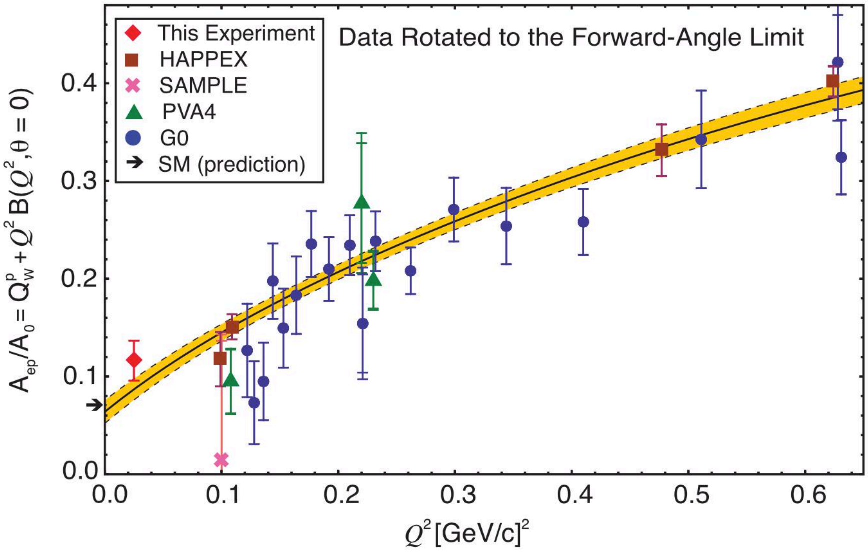


Figure 3.34: First proton weak charge result: a global fit to existing parity-violating asymmetry data rotated to the forward angle limit, with uncertainty indicated by the yellow error band. The Qweak 4% measurement is the lowest Q^2 data point. The intercept at $Q^2 = 0$ is the proton's weak charge. The SM value is indicated by the black arrow [Androic *et al.*, Phys. Rev. Lett. 111, 141803 (2013)].

The Canadian group has played a major role in this international effort, at roughly 15% of the collaboration. Total NSERC support for the project was \$ 3.4M, including \$ 0.7M towards construction of key elements of the hardware, including fabrication of the water-cooled copper conducting coils and holders for the Qweak spectrometer, development and instrumentation of a novel diamond microstrip detector for the Hall C Compton polarimeter, and a small quartz scanning detector used to map the event distribution across the Qweak main detector bars. Major contributions of the Canadian group also included responsibility for the Qweak main detectors, developing a framework for systematic error analysis associated with helicity correlated beam properties, and work on the tracking system simulation and analysis.

Parity-violating electron-electron scattering: MOLLER at JLab (JLab) Manitoba, UNBC, Winnipeg; USA.

MOLLER will make a very high precision measurement of the parity-violating asymmetry in the scattering of longitudinally polarized electrons off unpolarized electrons, using the upgraded 11 GeV beam in Hall A at Jefferson Laboratory. The prediction for the asymmetry A_{PV} for the MOLLER design is ≈ 35 ppb, and the goal is to measure this quantity with a fractional accuracy of 2.1%. Polarized electron scattering off unpolarized targets provides a clean window to study weak neutral current interactions. At the goal precision, this measurement will constitute a factor of almost 5 improvement in uncertainty over the only other measurement of the same quantity (the E158 experiment at SLAC), providing a high precision measurement of the weak charge of the electron, $Q^e_W = 1 - 4\sin^2\theta_W$, and therefore of the weak mixing angle, with $\delta(\sin^2\theta_W) = \pm 0.00029$. This will be comparable to the two best such determinations from the $e^+ - e^-$ colliders LEP and SLC. Due to the precise theoretical predictions of the weak mixing angle within the Standard Model, the MOLLER experiment is sensitive to physics beyond the Standard Model at the TeV scale, at the level of $\approx 10^3\, G_F$. For purely leptonic amplitudes, MOLLER will be accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory. Some examples of specific models where MOLLER has a strong sensitivity are doubly-charged scalars, heavy Z bosons and supersymmetric extensions to the Standard Model. Assuming a new resonance in this energy range is seen at the LHC, low-energy precision data will be essential to disentangle the couplings. This precision scattering experiment will require theory support, in order for its measurements to be meaningful. Some of this theory will be done in Canada, and is described in the chapter devoted to nuclear theory.

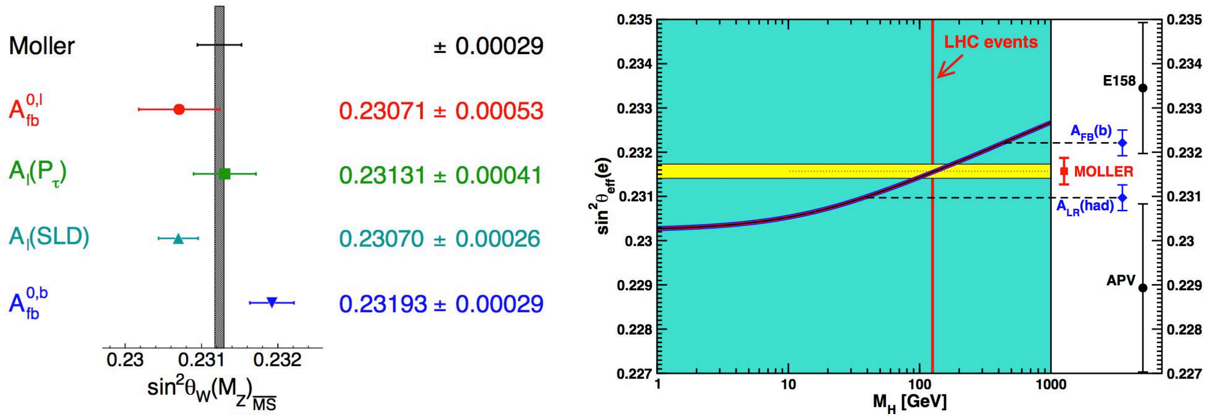


Figure 3.35: Left: The four best Weinberg angle measurements and the projected error of the MOLLER proposal. The black band represents the theoretical prediction for a Higgs mass of 126 GeV. Right: $\sin^2\theta_W$ vs. the Higgs mass. The yellow band is the world average. The blue data points are the two best high energy determinations. The black points are the two most precise measurements at $Q^2 \ll M_Z^2$. The projected MOLLER error is shown in red.

Two University of Manitoba faculty are package leaders and DOE level 2 managers for the spectrometer development and the integrating detector package. These core Canadian contributions form the minimum effort that needs to be maintained to produce an acceptable impact and benefit.

Atomic parity violation in laser-trapped francium at TRIUMF (TRIUMF) Manitoba; Mexico, USA.

In atoms, extremely weak electric dipole transitions between states of the same parity are induced by the parity-violating exchange of Z-bosons between the electrons and the quarks in the nucleus, an effect known as atomic parity violation (APV). By measuring this amplitude, one can study neutral-current weak interactions with atomic physics methods and search for new physics such as extra gauge bosons and leptoquarks. APV is strongly enhanced in heavy atoms, but the atomic structure calculations necessary to extract the weak physics are presently only feasible in alkali atoms. In francium, the APV effect is 18 times larger than in Cs. However, Fr has no stable isotopes, must be produced at a radioactive beam facility such as TRIUMF's ISAC, and needs to be accumulated in a laser trap. Since 2011, the international FrPNC collaboration (Canada, USA, Mexico) has established the francium trapping facility at ISAC. An electromagnetically hermetic room shields the laser and microwave setup from electric interference. A magneto-optical capture trap receives Fr isotopes from ISAC, and confinement of up to $\approx 10^6$ atoms of a single Fr isotope in a volume of ≈ 1 mm^3 at micro-Kelvin temperatures has been demonstrated. As part of the commissioning process, 7 isotopes and 1 isomer were trapped and isotope shifts and hyperfine anomalies precisely measured. In 2014, the transfer of the trapped atoms into a secondary 'science chamber' was demonstrated. It provides a radioactively clean environment with well controlled electric and magnetic fields, a requisite for APV work. Spectroscopy of the 7s-8s Stark-induced transition commences in 2016. By 2018 observation of the nuclear-spin independent APV signal is expected. After initial studies of systematics, long statistics runs will take place, enabled by ARIEL's capability to deliver multiple beams simultaneously.

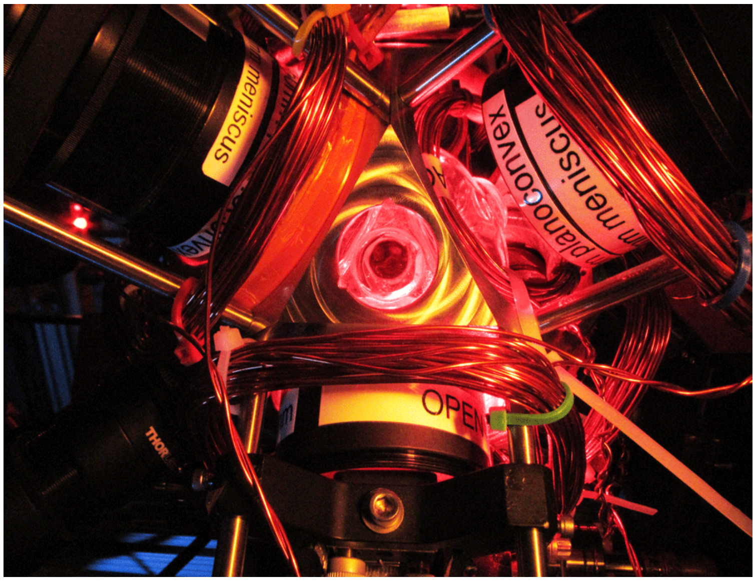


Figure 3.36: The francium capture trap.

3.4.2.3 CPT and Lorentz violation

CPT invariance and Lorentz symmetry are at the very foundation of our current description of nature, as quantum field theories are firmly based upon these principles. However, in string theory and also in quantum gravity, which unifies the Standard Model of particle physics with general relativity in a 'Theory of Everything', CPT and Lorentz violation are frequently assumed. As low-energy experiments are, relatively speaking, not that much further away from the Planck scale as are colliders, the former play a very significant role in this field, driven by the extreme precision that can be reached mostly with laser and microwave-based measurement techniques. Canada is strongly involved in the high-profile endeavor of antihydrogen trapping and antimatter spectroscopy. Canada provides the largest contingent by country in the ALPHA collaboration working at CERN. The competing ATRAP effort also has Canadian members, which are funded outside of the subatomic envelope.

In addition, an experimental program with involvement by the University of Manitoba, testing relativistic time dilation via laser-spectroscopy of Li^+ ions circulating in the storage rings TSR and ESR in Germany was concluded in 2014. The prediction of special relativity was confirmed, and limits on possible deviations reduced 50-fold compared to non-storage ring measurements.

CPT, Lorentz invariance and gravity tests with trapped anti-hydrogen: The ALPHA project at CERN (CERN) Calgary, SFU, TRIUMF, UBC, York; Brazil, Denmark, Israel, Sweden, Switzerland, UK, USA

The Antihydrogen Laser Physics Apparatus (ALPHA) is an international project at CERN, whose aim is to test fundamental symmetries between matter and antimatter using trapped antihydrogen atoms. ALPHA-Canada consists of about one third of the international collaboration. Antiproton physics is an internationally competitive field. A key distinguishing feature of ALPHA among the competing experiments is its aggressive application of subatomic physics techniques, including a 37,000 channel silicon vertex detector and modern machine-learning analysis algorithms. ALPHA-Canada is responsible for almost all of the subatomic aspects of the experiment, except for the production of silicon sensors. Other areas of unique Canadian expertise include microwave techniques and high-power, short-wavelength lasers. ALPHA-Canada scientists have been making direction-setting contributions in the project, including development of detection techniques for trapped antihydrogen, establishment of its long-time confinement, demonstration of first spectroscopy via microwaves, the proposal for a charge neutrality measurement, the implementation of pulsed laser cooling, and most recently, driving the effort to construct a new vertical trap, now called ALPHA-g, for gravity studies.

Following the successful demonstration of antihydrogen trapping, and the Canadian-led, world-first anti-atom spectroscopy, a new apparatus, ALPHA-2, was constructed, featuring optical access to the trapped antihydrogen to allow laser spectroscopy and cooling. In the 2015 run, a concerted campaign for laser spectroscopy of antihydrogen atoms, with both the European-led 1s-2s two-photon spectroscopy, and the Canadian-led 1s-2p Lyman-alpha spectroscopy and cooling is started. ALPHA-2 was designed to be operational for up to 10 years, enabling spectroscopic tests of CPT with increasing precision.

ALPHA-g is a new initiative whose ultimate goal is to make precision measurements on the gravitational interaction of antimatter and the Earth. While there are a number of indirect arguments against any gravitational asymmetry between matter and antimatter, there is no direct measurement of gravity's effect on antimatter - no one has seen antimatter fall down. CFI support for the project has just been announced. Together with the anticipated provincial and institutional matching, more than 80 % of the entire ALPHA-g infrastructure will be funded by Canada, making it truly a Canadian-led international project. It will proceed in stages: (1) the initial measurement of the sign of antimatter gravity, i.e. does antimatter fall up or down, (2) a 1% level measure-

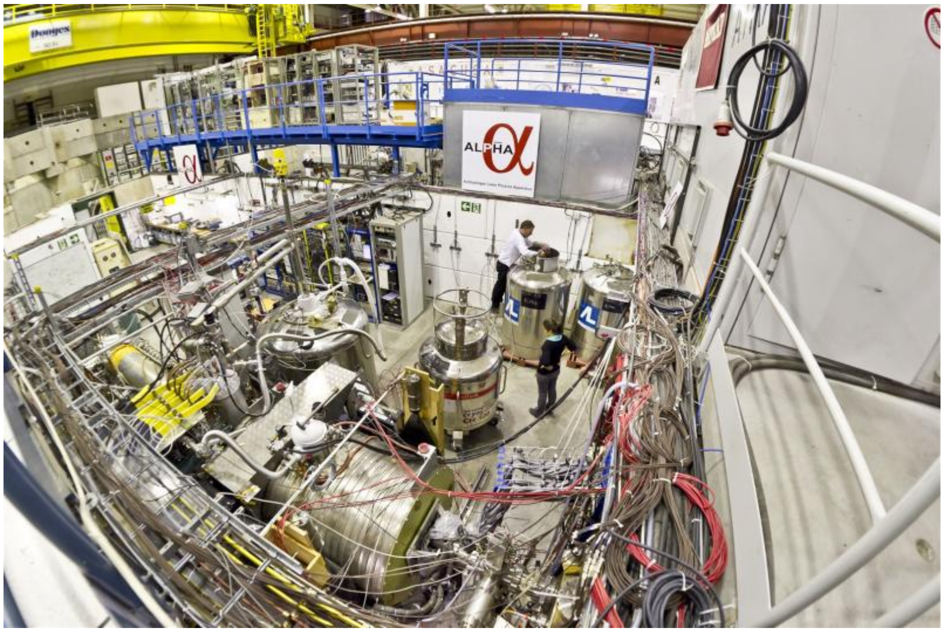


Figure 3.37: The ALPHA setup at CERN.

ment of the gravitational acceleration using laser-cooled antihydrogen, and (3) the development of anti-atom interferometry techniques, which would open up the potential for a 10^{-6} measurement. ALPHA-2 and ALPHA-g will greatly benefit from the new ELENA facility, an upgrade to the AD ring, which will enable an increase in the number of trapped antiprotons by up to 2 orders of magnitude.

Over the past few years, ALPHA has produced several Nature publications, and the ALPHA-Canada team members and their students have been recognized with various prestigious awards, including the 2013 NSERC John C. Polanyi Award for outstanding advances in science and engineering, the 2011 John Dawson Award by the American Physical Society, and the CAP-DNP Thesis Award.

3.4.2.4 Unitarity of the Cabibbo-Kobayashi-Maskawa matrix

Precision measurements of the ft values for superallowed $0^+ \to 0^+$ Fermi β decays provide demanding tests of the Standard Model. Such measurements have, for example, confirmed the conserved vector current (CVC) hypothesis at the level of 1.2×10^{-4}, set the most stringent limits on fundamental weak scalar interactions at $(0.14 \pm 0.13)\%$ of the vector strength, and, together with the Fermi coupling constant G_F from muon decay, provide the most precise determination of the $V_{\rm ud}$ element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. A significant uncertainty in these tests, however, arises from the theoretical nuclear structure corrections, δ_C, that are required to account for the breaking of isospin symmetry by Coulomb and charge-dependent nuclear forces, motivating a wide range of theoretical approaches to these isospin symmetry breaking corrections over the past decade. To test and constrain these theoretical models, and to ultimately have confidence in the CVC test and the value of the $V_{\rm ud}$ matrix element, high-precision experimental superallowed β decay data are very important.

Precision measurements on superallowed β emitters at TRIUMF (TRIUMF) Guelph, Queens, SFU, Toronto, UBC; UK, USA.

The Canadian community working at the TRIUMF-ISAC facility is uniquely positioned for scientific impact in this field, as ISAC produces high-quality beams of many of the superallowed β emitters with world-record intensities and also hosts a suite of state-of-the-art spectrometers capable of precision measurements of all of the experimental quantities of interest in superallowed decays. These include high-precision half-life measurements through both β counting with the 4π gas proportional counter at the ISAC-I GPS facility and γ-ray counting with the 8π spectrometer (and now GRIFFIN), high-precision branching-ratio measurements with the 8π/GRIFFIN and associated detectors, high-precision superallowed Q-value measurements with the TITAN mass spectrometer (^{74}Rb and ^{10}C), and charge-radii measurements through collinear laser spectroscopy at ISAC (^{74}Rb) required as input to the isospin symmetry breaking calculations.

At the 8π spectrometer, in the past few years, high-precision measurements of the half-lives of the three lightest superallowed emitters, ^{18}Ne, ^{14}O, and ^{10}C proved to be important in establishing limits on weak scalar currents. At the GPS facility, ^{38m}K, ^{26m}Al, and ^{10}C half-lives were determined to $\approx 0.01\%$ precision. Notably, the result for ^{26m}Al with a precision rivalling that of all the other thirteen precisely measured superallowed decays combined set a new benchmark for testing models of isospin symmetry breaking in nuclei [P. Finlay *et al.*, Phys. Rev. Lett. **106**, 032501 (2011)].

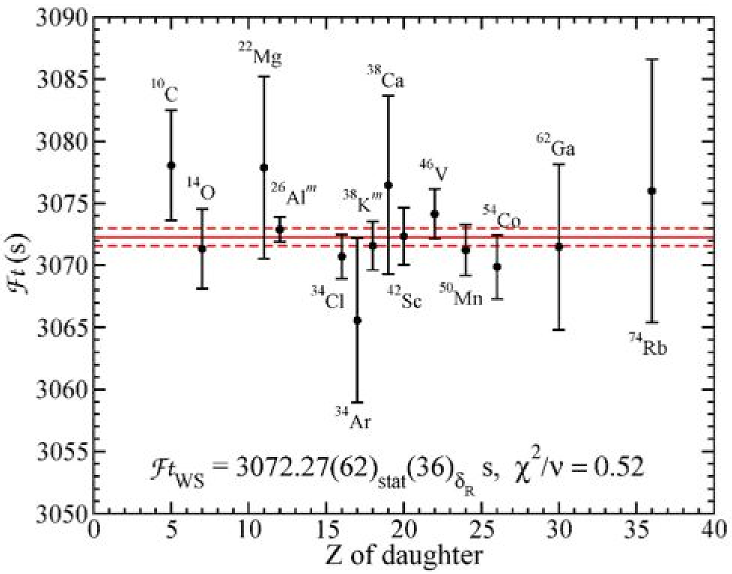


Figure 3.38: Corrected Ft values for the 14 precisely measured superallowed Fermi β decays from [J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)]. These data confirm the conserved vector current hypothesis at the level of 1.2×10^{-4} and provide the most precise determination of the V_{ud} element of the CKM quark mixing matrix.

This program will continue to be developed at ISAC throughout the 2016-2021 period. In particular, the high efficiency of the new GRIFFIN spectrometer will be used to perform precision branching ratio measurements for the $N = Z - 2$ superallowed emitters ^{22}Mg and ^{34}Ar, the latter providing a clean isolation of specific components of the isospin symmetry breaking corrections through comparison with the analogue superallowed decay of ^{34}Cl. The $300 - 500$ fold increase in $\gamma - \gamma$ coincidence efficiency provided by GRIFFIN will revolutionize precision superallowed branching ratio measurements for the $A \geq 62$ decays, ultimately to be expanded to the first precise measurements for the heavy superallowed emitters ^{66}As and ^{70}Br as new beams are developed at ISAC. Finally, during the 2016-2021 period, the program of high-precision half-life and branching-ratio measurements at ISAC will be expanded to include isospin $T = 1/2$ mirror nuclei such as ^{35}Ar and ^{15}O, which currently provide the second most precise determination of the V_{ud} matrix element and an independent test of the CVC hypothesis.

3.4.2.5 Beta neutrino correlations with trapped atoms and ions, and cold neutrons

Particle traps are ideal tools for studying correlations in β decay. The nuclear recoil escapes freely from the trap (i.e. there is no backing material), and its momentum and that of the beta can be measured, so the neutrino momentum can be determined. Furthermore, the nuclei can be spin-polarized by atomic optical pumping methods to an extremely high degree, and can be probed by atomic methods independent of the nuclear decay. Correlation experiments set stringent limits on potential scalar and tensor weak currents, and can also be used to constrain more exotic physics. Canada is a world leader in this line of research. The TRINAT facility at TRIUMF has pioneered the use of neutral atom traps to measure beta decay correlations. In the past few years, the Canadian Penning Trap collaboration has successfully added a Paul ion trap-based system at Argonne. The *Nab* experiment at Oak Ridge will also pursue correlation and Fierz interference measurements using cold, polarized neutrons.

The TRINAT neutral atom trap at TRIUMF (TRIUMF) Manitoba; Israel, USA.

The Standard Model predicts the angular correlations between β, ν, and the initial spin, mainly from the helicity of the leptons made in the weak interaction, and measurements at 0.001 accuracy probe new physics contributions with sensitivity complementary to rare decay and high-energy collider experiments. Many of the decay asymmetries are perturbed linearly by interference between the Standard Model and new physics amplitudes, which allows beta decay experiments to remain competitive to direct particle production and precision high-energy cross-section measurements in $p + p \to e + \nu + X$.

The beta-neutrino correlation in ^{38m}K, one of the pure Fermi $0^+ \to 0^+$ decays, is sensitive to scalar interactions only. TRINAT has performed the best measurement in such a system and is working on an order of magnitude improvement. This will provide the best direct sensitivity to scalar interactions coupling to wrong-helicity neutrinos, and will be competitive with constraints on the Fierz scalar-vector interference term from dependence of the world-average $0^+ \to 0^+$ strengths on energy release.

The experiment on spin-polarized ^{37}K decay can now determine the polarization of the decaying nuclei by atomic methods, contributing uncertainty 0.001 to correlation observables. Statistics for a 0.002 measurement of the beta asymmetry with respect to the nuclear spin has been collected. Planned are similar measurements of the asymmetry of the final nuclei, with projected uncertainty 0.002 on tensor interactions per week of counting. ^{37}K decay by mixed Fermi/Gamow-Teller operators to its isobaric analog is a case where higher-order corrections are mostly known from measurements of electromagnetic moments and CVC. TRINAT is becoming competitive with neutron beta decay on this front.

The Beta Paul Trap at the Canadian Penning Trap facility at Argonne (Argonne) Manitoba, McGill; USA.

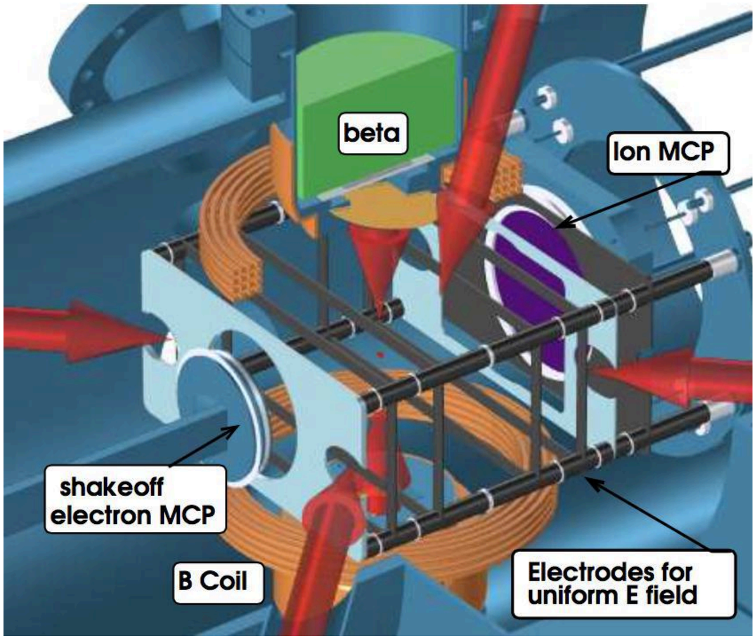


Figure 3.39: The new TRINAT laser trap chamber for next-generation decay correlation experiments.

An open geometry radio frequency quadrupole trap has been installed behind the Canadian Penning Trap's original target and gas catcher system. It is used to study $\beta - \nu$ correlations in ^{8}Li and ^{8}B. The $2^+ \rightarrow 2^+$ decay of ^{8}Li into ^{8}Be with a subsequent break-up into two α particles is essentially pure Gamow-Teller with a Fermi-admixture of only $(5.0 \pm 1.5) \times 10^{-4}$, i.e. there are only axial and potential tensor contributions. The half-life of 840 ms is convenient for traps, and the large Q-value of 16 MeV and the small nuclear mass produce a large nuclear recoil of 12 keV. As a result, large kinematic shifts are imparted on the break-up α particles. The ≈ 1 mm^3 ion cloud is surrounded by arrays of double-sided silicon strip detectors (DSSD) used to determine the β's momentum direction and both the energies and the momenta for the α particles. While not required, plastic scintillators can measure the β energies as well, over-constraining the kinematics. First results have already been published [Li *et al.*, Phys. Rev. Lett. 110, 092502 (2013)]. An improved constraint $|C_T/C_A|^2 < 0.005$ will soon be published, in addition to results from ^{8}B decay. Future plans aim at a sensitivity at the 0.001 level.

The Nab neutron beta decay experiment at the Spallation Neutron Source (Oak Ridge) Manitoba, Winnipeg; USA.

The *Nab* experiment will measure the $e - \nu$ correlation parameter a and the Fierz interference term b in polarized neutron beta decay with an accuracy of a few parts in 10^3 using a novel field-expansion spectrometer. The b term is predicted to be zero, and the proposed measurement, being the first to measure this quantity, will produce an upper limit on its value. The measurement of angular correlations in neutron β-decay provides the most sensitive means to evaluate the ratio of axial to vector coupling constants $\lambda = g_A/g_V$. The precise value of λ is very important in many applications of the theory of weak interactions, especially in astrophysics, e.g. a star's neutrino production is closely related to λ^2. It is also important in the search for physics beyond the Standard

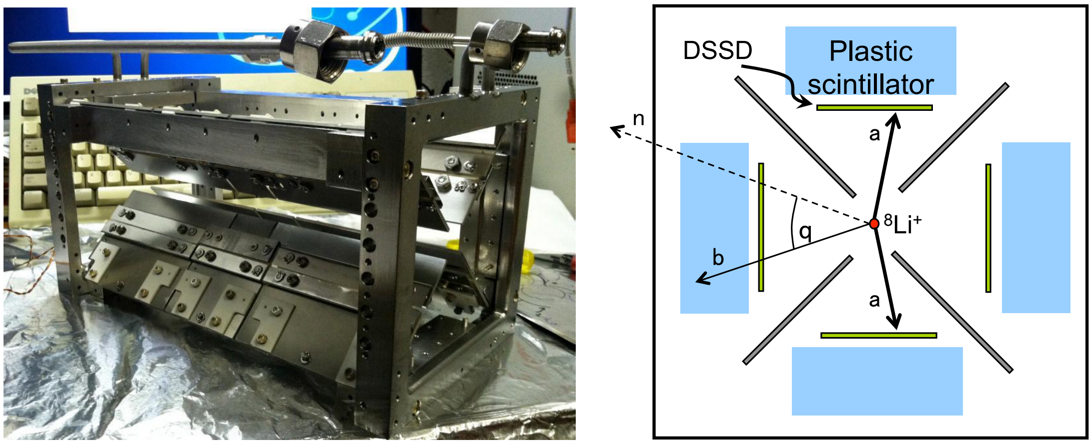


Figure 3.40: Left: The Beta Paul Trap at Argonne. Right: DSSD arrays and plastic scintillators surround the decaying ^{8}Li$^+$ ions in the center of the trap.

Model. An independent measurement of λ is necessary in order to determine the CKM matrix element $V_{\rm ud}$ from the neutron lifetime. To date, the most accurate value has been obtained from measurements of superallowed nuclear β-decays, ($V_{\rm ud} = 0.97417(21)$). However, the extraction of this value involves calculations of radiative and nuclear structure corrections for the Fermi transition in nuclei. The interpretation of results from neutron beta decay measurements are free of nuclear corrections and are therefore highly complementary. The value for $V_{\rm ud}$ from neutron beta decay is 0.9773(24), which is based on the most recent neutron lifetime measurements. For some time, the best precision by far in extracting λ has been achieved through measurements of the asymmetry parameter A, the correlation between the electron momentum and the neutron spin. However, the experimental status of A and λ is far from satisfactory, with a signficant discrepancy between the two most accurate measurements to date. The *Nab* experiment aims at resolving this situation.

The muon anomalous magnetic moment $(g-2)$ at J-PARC (J-PARC) TRIUMF, UBC, Victoria; Japan.

The observed discrepancy between the Brookhaven National Laboratory E821 measurement and the Standard Model prediction of the muon anomalous magnetic moment, $a_\mu = (g-2)/2$, may suggest new physics. After many years of scrutiny, the challenging calculations of corrections and uncertainties to the Standard Model value of a_μ still indicate a disagreement with experiment at the $3.6\,\sigma$ level. The experiment will be repeated at Fermilab (E989), using the same method and in fact the same muon storage ring as BNL E821. A new and different experiment at J-PARC (E34), shown in Fig. 3.41 will be susceptible to different systematic effects than the Brookhaven/Fermilab experiments. From an intense beam of over 10^8 polarized μ^+ per second at 28 MeV/c, from pions produced by the 1 MW 3 GeV pulsed proton beam, E34 will produce a beam of 0.3×10^6 polarized μ^+ per second at room-temperature thermal energies from resonant ionization of muonium in vacuum. Following subsequent acceleration to 300 MeV/c, this relatively smaller number of μ^+ has extremely low transverse and longitudinal energy spreads (order 1 eV), so that the beam can be injected and stored in the 3 T field of a ring of only 0.66 m diameter. Unlike the BNL/Fermilab method, the storage ring uses no focusing electric fields so that storage ring parameters such as momentum may be chosen independently. Muon decays will be measured by tracking detectors within the storage radius. In a first stage of the experiment, a precision of 0.36 ppm is envisioned, compared to 0.46 ppm for BNL E821 for a_μ. In addition, the sensitivity to a permanent electric dipole moment is increased to 1.3×10^{-21} e-cm (BNL E821: 0.9×10^{-19} e-cm).

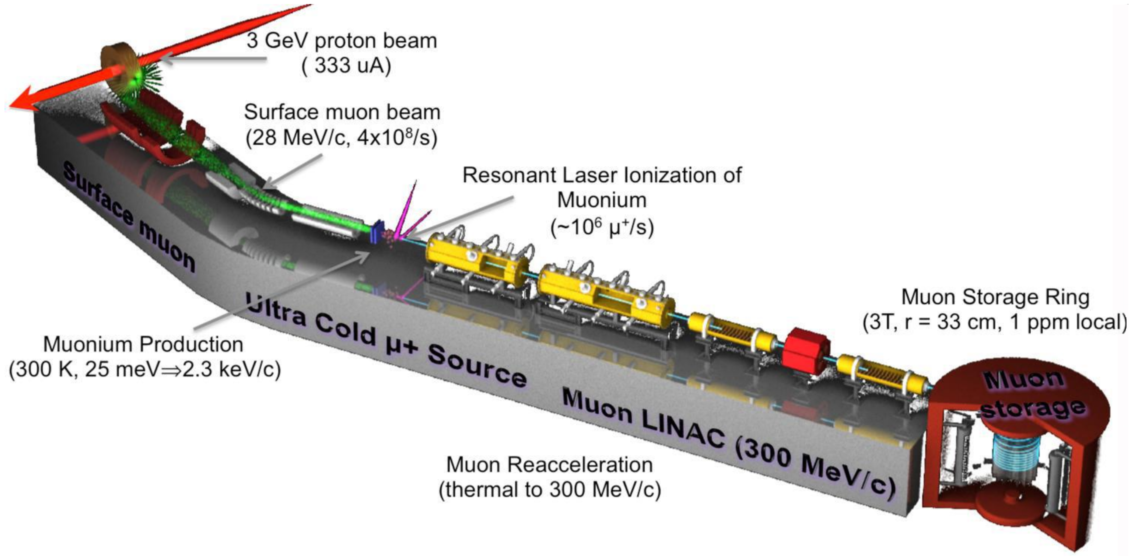


Figure 3.41: The muon g-2 experiment at J-PARC.

3.4.2.6 Neutrinoless double β-decay

A major open question is the nature of neutrinos and how they influence the evolution of the universe. The discovery that neutrinos are not massless has been transformative in that a neutrino could have an astonishing property of being its own anti-particle. An extremely rare nuclear decay mode known as neutrinoless double beta decay offers the only viable experimental method to test for this possibility. The observation of this most exotic decay mode would provide irrefutable evidence that neutrinos are their own anti-particle and correspondingly that the symmetry of lepton number conservation is violated. Its observation would also provide strong experimental guidance for theories that go beyond the Standard Model, yielding insights into the origin of the neutrino mass. In particular, if neutrinos are their own antiparticles, they could not gain their mass through the interactions with Higgs particles in the same way as all other elementary particles in the Standard Model. Neutrinos with this property could also be key players in generating the excess of matter over antimatter.

The experimental task is extremely daunting as the experiments are probing decay half-lives on the order of 10^{26} to 10^{28} years, require unprecedented purity of materials to reduce potential backgrounds from naturally occurring radioisotopes.

The EXO-200/nEXO experiments (WIPP/SNOLAB) Carleton, Laurentian, McGill, SNOLAB, TRIUMF; China, Germany, Russia, South Korea, Switzerland, USA.

The Canadian community is heavily involved in the EXO-200 experiment, which currently operates a 200 kg liquid xenon detector at the WIPP facility in New Mexico and plans to develop a 5 tonne detector, nEXO at SNOLAB. In 2011, the collaboration made the first observation of the two-neutrino double β-decay in the isotope ^{136}Xe [Phys. Rev. Lett. 107, 212501 (2011)], and was able to show, for the first time [Phys. Rev. Lett. 109, 032505 (2012), Nature 510, 229 (2014)], that the observation claimed by Klapdor-Kleingrothaus was very unlikely to be correct, and this has now been confirmed by others. To reach sensitivities to a half-life beyond 10^{26} years, and to probe increasingly smaller neutrino masses will require much larger, tonne scale, experiments. The EXO Collaboration is now working towards the design of the 5 tonne nEXO detector and is proposing to site it at SNOLAB. The timescale for the establishment of nEXO is driven by the U.S. decision making process, and a final down-select is expected in 2017, followed by a construction period of $\approx$ 5 years.

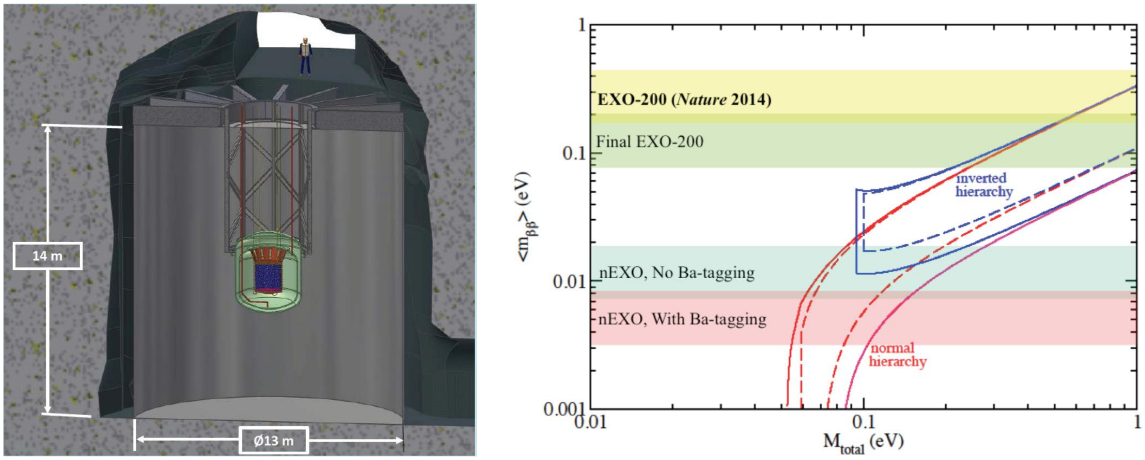


Figure 3.42: Left: Schematic diagram of the nEXO detector in the SNOLAB Cryopit. Right: The achieved and expected sensitivities for the nEXO project. The effective Majorana mass is plotted against total mass, for the mean values of oscillation parameters (dashed) and for the 3σ errors (full). In the barium-tagging mode, much of the normal hierarchy is probed.

The larger detector will inherit much of the design of EXO-200, with exceptions such as a lower-activity water shield instead of lead. A sketch of nEXO is given in Fig. 3.42, shown located in the Cryopit at SNOLAB.

Canadians have a substantial impact in EXO-200, including calibration systems, radon control, process system design concepts, veto system mechanical construction, and materials testing through ultra-trace assays. Canada also plays a major role in the nEXO project, managing the simulations and photosensor groups, and being responsible for radon abatement and assay and calibration systems with external sources. In particular, the Canadian team is taking a lead in the development of barium tagging, which might form the basis of the next generation of detectors which control the background by only including events in which a barium ion is produced.

The right panel in Figure 3.42 illustrates how nEXO may enable the first measurement of the effective Majorana mass, near the astrophysical neutrino mass constraint of $\approx$ 20 meV. Particularly if barium-tagging can be shown to work at the requisite level, the nEXO data sample would be exceptionally clean and sensitive to the neutrinoless decay, giving it a substantial advantage over competing experiments.

3.4.3 The next five years (2016-21)

Over the next five years, several proven efforts will continue to push the limits and new ones will come online. The superallowed β decay program at TRIUMF will profit from the development of the new GRIFFIN gamma-ray spectrometer and new beam developments at ISAC will allow additional $0^+ \to 0^+$ emitters to be measured with high precision. The TRINAT neutral atom trap facility will benefit from the new science chamber, pushing β correlation measurements to the 0.001 level; a novel triple-correlation measurement sensitive to T-violation will be demonstrated. Similarly, the ion-trap β correlation experiment at Argonne will push to 0.001 accuracy for Gamow-Teller decays. The francium trapping facility at TRIUMF will start precision spectroscopy of the highly forbidden 7s - 8s transition in 2016 and aims for observing the parity-violating amplitude by 2018. The ALPHA collaboration will continue their quest to perform precision spectroscopy on antimatter, and start the first measurements on antimatter gravity. The new ELENA facility will come on-line at CERN in 2018. The UCN project at TRIUMF will start to operate their ultra-cold neutron source and carry out a first neutron EDM measurement. By 2017, MOLLER will enter the construction phase, taking the baton from the Qweak effort, which will announce its final value for the weak charge of the proton in 2016. By 2018, the *Nab* experiment will produce data and J-PARC's E34 muon $g-2$ experiment in 2019. With help of the GRIFFIN array, nuclear structure in $^{221.223}$Rn will be elucidated in preparation of a Rn EDM measurement. Prior to the anticipated start of construction in 2017, nEXO will prepare for the launch of the 5 tonne detector and pioneer the barium tagging method.

3.4.4 Long-range vision (2022-26)

Most fundamental symmetries experiments are long-term investments. In the coming five years, a broad range of new initiatives unfolds, and the fruits of this work will become apparent within the 10-year horizon. ALPHA will be deep into its campaign to deliver antihydrogen laser and microwave spectroscopy on par with what is possible today in regular hydrogen, yielding model-independent, unambiguous tests of CPT invariance. ALPHA-g will perform precision measurements on antimatter gravity. Phase 2 of the UCN nEDM experiment at TRIUMF will produce a new, significantly improved limit on the neutron EDM. The next-generation electron scattering experiment, MOLLER, will produce the most precise low-energy data, and provide stringent tests of purely leptonic weak neutral currents. J-PARC E34 will either have settled the muon magnetic moment anomaly, or strengthen the case for new physics. By 2022, nEXO can be expected to go online. Barium tagging will allow it to probe deep into the normal hierarchy territory by the end of the 10 year period.

The completion of the ARIEL project at TRIUMF will have a profound impact by enabling up to three simultaneously delivered radioactive beams. Several fundamental symmetries experiments will be able to receive enough beam for longer, statistics-gathering campaigns: atomic parity violation in francium, to improve our knowledge of weak electron-quark couplings; TRINAT pushing the limits on T-violating triple correlations, complementary to EDM searches; and RnEDM with the GRIFFIN array. In addition, a francium EDM experiment should become operational, to provide competitive limits on the electron's EDM derived from a simple, atomic system.

3.4.5 Summary

The Canadian nuclear physics community is involved, and in many cases is heading, world-leading efforts in the area of fundamental symmetries. The record over past decade has been excellent, and several major, exciting new initiatives will enter the stage over the next five years, ensuring Canadian leadership well beyond a 10-year horizon. The program is remarkably balanced in terms of work at Canada's own world-class facilities, TRIUMF and SNOLAB, versus off-shore projects. The scientific coverage is amazingly diverse, addressing the pressing questions in the field. Research in fundamental symmetries of nature is undoubtedly one of the jewels in Canadian science.

3.5 Nuclear Theory

3.5.1 Overview

The theory of the atomic nucleus, of its structure, of the interaction between its constituents, and of their own structure is quantum chromodynamics (QCD). As this theory is non-conformal, the nuclear interaction appears to be quite different at different energy scales. At high energies most QCD calculations are amenable to perturbative techniques. However, at the energy scale where the details of nuclear structure are relevant, QCD is non-perturbative. Lattice techniques, in their current realization, can not solve all problems in hadronic physics. However, there has been remarkable recent progress in effective theories which preserve the important symmetries of the underlying fundamental theory, and yet are applicable in a given energy interval. However, for a large class of problems, phenomenological approaches to methods and modelling are required. The role of models, especially in strong-coupling problems such as those most relevant to nuclear physics, has been crucial for the development of the theories. However, while phenomenological approaches continue to play an important role it is a primary focus of effort to pursue theoretical descriptions which are derived from first principles.

Progress in nuclear theory, both from a fundamental point of view, and in its connection with experimental measurements has therefore to proceed on several fronts at once. It is imperative to maintain a vibrant and diverse theoretical program at the top level. The Canadian community is doing exactly this, and as such nuclear theory research in Canada has emerged as a world-leading effort.

3.5.2 The Canadian program

Canadian theorists have kept at the forefront of the rapidly developing trends in nuclear and hadronic theory with many examples of close involvement in the major break-throughs of the field. The Canadian effort is distributed in several groups across the country which are pursuing a broad program of initiatives.

There is a very active Canadian community pursuing a plethora of research topics on the theoretical aspects of QCD and of hadronic systems. Importantly, calculations involving QCD appear not only in nuclear physics, but in all computations and estimates that rely on the Standard Model such as calculating decay modes of the Higgs boson. In several cases, the overall precision is often determined by our knowledge of the strong interaction. In this section we highlight some Canadian activity in the theory of hot and cold QCD.

The Canadian community is also spearheading developments for the capability to theoretically describe light- and medium-mass nuclei as systems of nucleons interacting by forces rooted in the fundamental theory of strong interactions. Using a low-energy expansion of QCD, namely chiral effective field theory (χEFT), one can derive forces among nucleons and their interactions with external probes in a consistent way. Studies in light- and medium-mass nuclei are crucial to test such a theory and these initiatives are pursued hand-in-hand with experiments performed both at TRIUMF-ISAC and elsewhere.

Nuclear Theory research represents a great opportunity to reinforce an established Canadian strength that is clearly at the forefront of modern research.

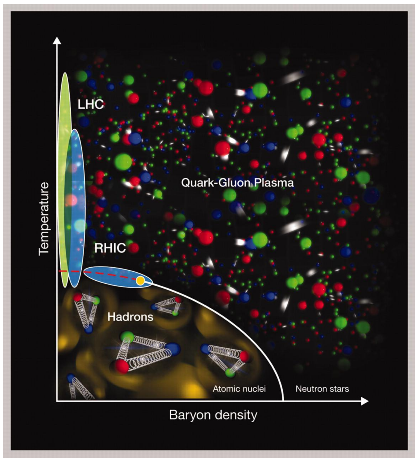


Figure 3.43: The conjectured phase diagram of quantum chromodynamics. Details are given in the text. This figure is from [B. V. Jacak and B. Müller, Science 337, 310 (2012).]

3.5.2.1 QCD under extreme conditions

The collision of large nuclei at high energy is a practical way of creating strongly-interacting systems at high temperatures and at high densities. These conditions prevailed a few microseconds after the Big Bang, and several experimental facilities around the world have been devoted to the study of "extreme QCD". Apart from the reproduction of the physical environment that existed in the early Universe, the many-body nature of finite-temperature QCD is still not that well known and many questions remain. For example: What is the nature of the QCD phase diagram? Are there critical points? What are the bulk properties of the quark-gluon plasma? Some of those questions have immediate relevance not only for hadronic physics, and answering them may also very well influence our understanding of the physics of dense stellar objects such as neutron stars. Figure 3.43 shows our current knowledge of the QCD phase diagram in terms of the aspects that are established, and of those that are surmised. At zero net baryon density, the transition from confined hadronic degrees of freedom to partonic ones has been established as a rapid cross-over, as opposed to a *bona fide* phase transition, and this fairly sharp transition has been calculated on the lattice to occur roughly at $T_c \sim 154$ MeV [Y. Aoki *et al.*, Phys. Lett. B 643, 310 (2006)]. The plot also shows the dynamical trajectories followed by the early universe (in light green), and by colliding systems at RHIC and at the LHC. At higher densities, a variety of effective models predict a first-order phase transition, opening up the possibility for critical points to exist at some intermediate value of density and temperature. The search for possible critical points is one of the purpose of the beam energy scan (BES), currently under way at RHIC.

One of the achievements of the relativistic heavy-ion program at RHIC, that has been spectacularly confirmed at the LHC, is the establishment of relativistic fluid dynamics as a successful modelling paradigm [C. Gale *et al.*, Int. J. Mod. Phys. A28, 1340011 (2013)]. An assessment of the collectivity in relativistic heavy-ion collisions is provided by the analysis of *collective flow*, as extracted from a Fourier expansion of the triple-differential distribution:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Psi_{\rm RP})\right]\right) \tag{3.2}$$

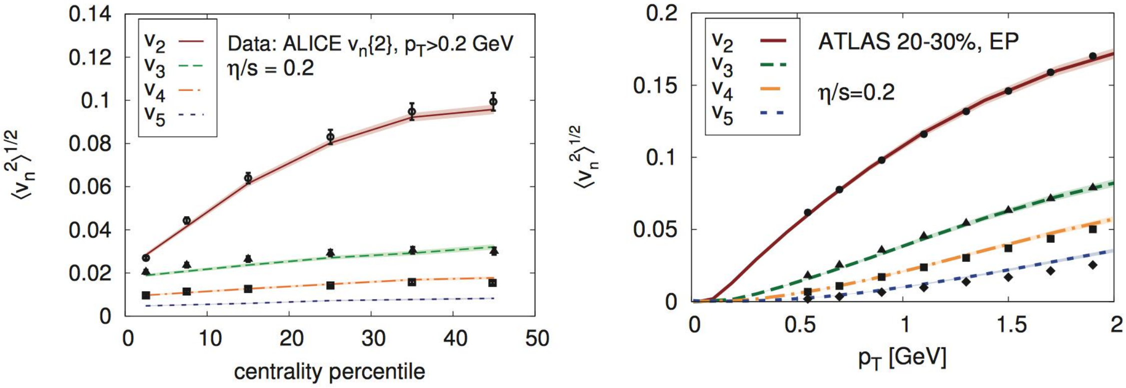


Figure 3.44: The root-mean-square anisotropic flow coefficients, computed with dissipative, relativistic fluid dynamics. The right panel shows the coefficients as a function of transverse momentum, for a given centrality class (a low centrality percentage indicates an almost head-on collision). The left panel show the momentum-integrated coefficients as a function of centrality. The data points are from the ALICE and ATLAS collaborations, at the LHC. This figure is from [C. Gale *et al.*, Phys. Rev. Lett. 110, 012302 (2013)].

where E and p_T are the particle energy and transverse momentum, y is the rapidity, ϕ is the azimuthal angle, and $\Psi_{\rm RP}$ is the reaction plane angle. The flow coefficients, v_n, can be measured and compared with theoretical calculations. From such comparisons, the transport coefficients of QCD such as the shear viscosity divided by the entropy density (η/s) can be extracted, as shown in Figure 3.44. The next generation of calculations will seek to attain greater accuracy, and will also aim to extract additional transport coefficients, such as the bulk viscosity and the heat conductivity of QCD. In parallel, a vigorous experimental program is continuing at RHIC and at the LHC, and will also start at FAIR/GSI, in Darmstadt, Germany, and at NICA, in Dubna, Russia.

3.5.2.2 The structure of QCD bound states

A great deal of theoretical effort is devoted to calculate bound states masses and transition matrix elements from a variety of approaches. Notably, Canadians have been pursuing the use of potential models and of lattice QCD techniques to calculate these quantities for states involving heavy quarks. An example of a calculation done in a relativistic quark model appears in Figure 3.45, and highlights a spectroscopy accessible to the Belle II, LHCb, and GlueX experiments. The meson results highlighted here were obtained with an approach which includes a relativistic kinetic energy term, together with a Lorentz vector one-gluon-exchange interaction, with a QCD-motivated running coupling constant, and a Lorentz scalar linear confining interaction.

Potential models represent a powerful and elegant non-perturbative technique to obtain bound state masses and decay transition rates. A first-principles approach to these results is that of lattice QCD. The Canadian lattice community is at work, obtaining non-perturbative results to compare with experimental measurements, or even making predictions for the results of observations yet to be performed. In this context, obtaining a lattice QCD value for the mass of baryons containing one heavy constituent quark has a theoretical advantage. Indeed, there the two lighter quarks can be treated using standard lattice techniques, and the heavy quark can be approached with non-

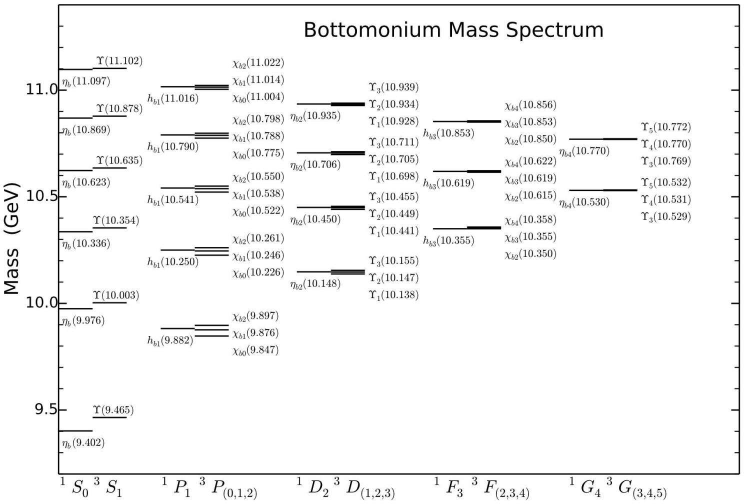


Figure 3.45: Predictions of the bottomium mass spectrum , as made with the relativized quark model [S. Godfrey and N. Isgur, Phys. Rev. D32, 189 (1985)]. This figure is from arXiv:1507.00024.

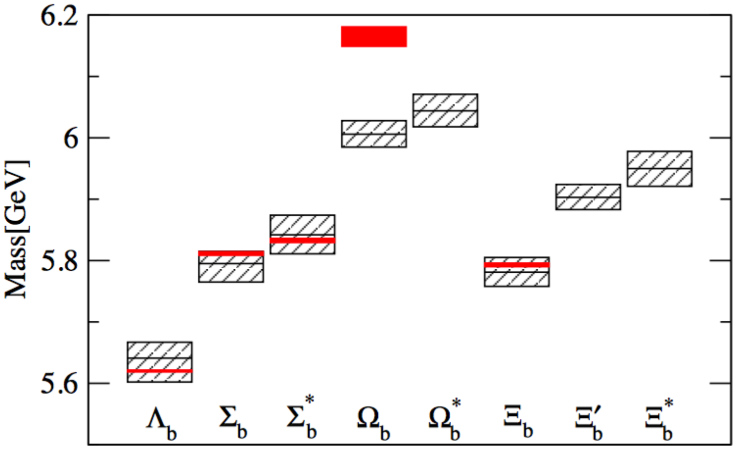


Figure 3.46: Masses of baryons with a single b quark. The hatched boxes represent the combined statistical and systematic errors in the lattice calculation. The measured masses are shown as the red boxes. This figure is from [R. Lewis and R. M. Woloshyn, Phys. Rev. D 79, 014502 (2009)].

relativistic lattice QCD (NRQCD). A example of this line of calculations is shown in Figure 3.46, where lattice results are shown together with experimental measurements when these exist. Notably, since the writing of the paper containing this figure (which has a 100% Canadian authorship) two of the states predicted have been measured – the Ξ'_b and the Ξ^*_b – and their masses are in agreement with the theoretical predictions, within uncertainties. The lattice result for those are (in GeV):

$$m_{\Xi_b'} = 5.903(12)\left(\begin{smallmatrix}18\\19\end{smallmatrix}\right), \quad m_{\Xi_b^*} = 5.950(21)\left(\begin{smallmatrix}19\\21\end{smallmatrix}\right),$$

where the parentheses show the uncertainty. The later measurements have been performed at the LHC by the LHCb collaboration. Their experimental results [Phys. Rev. Lett. 114, 062004 (2015)] are (in MeV):

$$m_{\Xi_b'} = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50, \quad m_{\Xi_b^*} = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50.$$

3.5.2.3 Synergies between neutron matter, cold atoms and nuclear ground states

Canadian researchers drew attention for the first time to the close analogies between low-density neutron matter (relevant to neutron stars) and cold gases (which are directly probed in experiments with fermionic atoms) [A. Gezerlis *et al.*, Phys. Rev. C 77, 032801(R) (2008); J. Carlson *et al.*, Prog. Theor. Exp. Phys., 01A209 (2012)]. By tackling the strong interactions and strong pairing correlations, it is possible to determine the equations of state (shown in Fig. 3.47) and pairing gaps, thus closely connecting these two very diverse systems. This allowed the use of information from cold-atom experiments to constrain nuclear theory, and therefore nuclear astrophysics, in a regime where all other (analytical or numerical) approaches are known to fail.

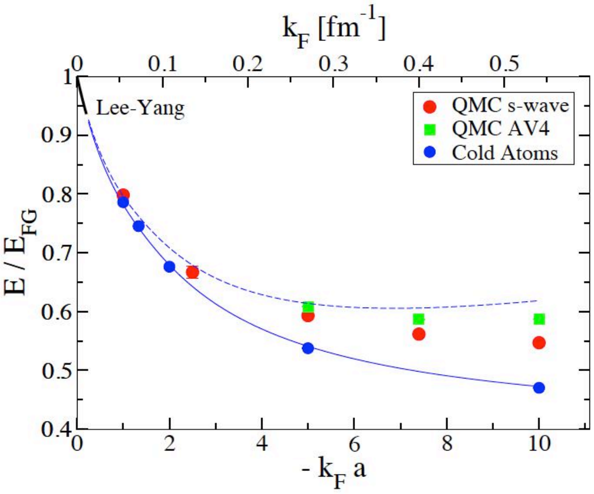


Figure 3.47: Quantum Monte Carlo results for the equation of state of low-density neutron matter compared to that of cold atoms at the same value of Fermi momentum times scattering length. Figure from Ref. [J. Carlson *et al.*, Prog. Theor. Exp. Phys., 01A209 (2012)].

Building on these developments, within a mean-field pairing formalism, nuclear ground-state wave functions were derived which support solutions in which the condensate is a mixture of spin-singlet and spin-triplet pairing [A. Gezerlis *et al.*, Phys. Rev. Lett. 106, 252502 (2011)]. The nature of pairing correlations is a long-standing problem in nuclear physics: the neutron-proton interaction is stronger than the neutron-neutron or proton-proton ones, yet nuclear systems are not known to exhibit neutron-proton pairing correlations. The work of Canadian researchers used a phenomenological Hamiltonian to make predictions for nuclei in the physical region that may be characterized by this new state of matter (mixed-spin pairing).

A crucial step was reported in reference [A. Gezerlis, *et al.*, Phys. Rev. Lett. 111, 032501 (2013)] where χEFT interactions were reformulated into a form that is amenable to use in continuum Quantum Monte Carlo methods. This allowed a fully microscopic local χEFT potential at three distinct orders in the potential expansion, and to apply all three in the context of the Auxiliary-Field Diffusion Monte Carlo (AFDMC) method. For the first time it was then possible to provide fully non-perturbative systematic error bands for the equation of state of neutron matter, as shown in Fig. 3.48 constructed from references [A. Gezerlis *et al.*, Phys. Rev. Lett. 111, 032501 (2013); A. Gezerlis *et al.*, Phys. Rev. C. 90, 054323 (2014); S. Gandolfi *et al.*, to appear in Ann. Rev. Nucl. Part. Sci. 65, (2015)]. The new local chiral approach is now being used for calculations of the properties of atomic nuclei, with first results reported in Ref. [J. E. Lynn *et al.*, Phys. Rev. Lett. 111, 192501 (2014)].

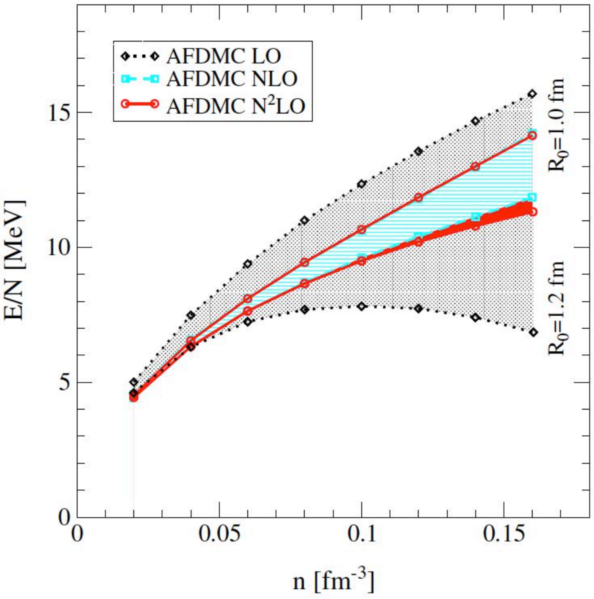


Figure 3.48: Neutron matter energy per particle as a function of the density, using Auxiliary-Field Diffusion Monte Carlo (AFDMC) with χEFT NN interactions at LO, NLO, and N2LO.

3.5.2.4 Studies on muonic atoms

In response to the "Proton-radius puzzle", Canadian researchers have developed a strong theoretical program to support the studies of muonic atoms at PSI, Switzerland. The size of the proton was measured via Lamb shift spectroscopy on muonic hydrogen obtaining a value which differs by 7σ from what was previously known from ordinary (electronic) hydrogen. This large discrepancy challenges our interpretation based on the standard model. New high-precision measurements are being conducted in other muonic atoms to extract the size of the nucleus. For this goal nuclear structure corrections need to be known very accurately. The TRIUMF theory group has recently performed the first ab initio calculations of nuclear structure corrections to the Lamb shift on muonic Helium [C. Ji *et al.*, Phys. Rev. Lett. 111, 143402 (2013)] and muonic Deuterium [C. Ji *et* *al.*, Phys. Lett. B 736 344 (2014)] with a precision of 6% and 1%, respectively. To constrain beyond-the-standard-model physics which could be at play and learn if new forces couple differently with the proton and the neutron, it is important to study nuclei with $Z \neq N$. In the near future, nuclear structure corrections will be addressed for muonic $^3\mathrm{He}^+$ and $^3\mathrm{H}$ which are systems where experiment investigations are planned. A longer-term objective is to study nuclear structure corrections to the hyperfine-splitting in muonic D and $^3\mathrm{He}^+$ using χEFT at various orders. These are dominated by magnetic transitions and will require the implementation of two-body currents in χEFT. These calculations will be instrumental to shed light on the proton-radius puzzle.

3.5.2.5 One and two-loop electroweak radiative corrections for electron-electron scattering

One way to obtain access to physics at multi-TeV scales is with high-precision electroweak experiments such as parity-violating Moller scattering, e^+e^- collisions or electron-nucleon scattering. These low-energy experiments tend to be less expensive than experiments at the high-energy colliders, but they are more model-dependent and require significant theoretical input, including not only NLO, but also NNLO radiative corrections. The low-energy sector is not as well served as the LHC, and there are no ready-to-use routines available for complete calculation of electroweak radiative corrections. The problem is that for electroweak processes, the full two-loop calculations face dramatic complications due to massive vector bosons in the two-loops integrals. In the long-term, the ultimate goal would be the evaluation of the full set of the electroweak one-loop and two-loop diagrams for scattering processes involving all particles of the Standard Model, as well as including new-physics particles at one-loop level.

The Memorial/Acadia group focuses on automatization of the computations.First comes the analytical evaluation of the tensor loop integrals and their reduction to scalar integrals using computer algebra (FeynArts, FormCalc, FORM) approaches in Mathematica, followed by the automatic generation of the Fortran code and numerical integration. The first stage yields analytical expressions, which can be used for a broad range of kinematical conditions, while the second stage deals only with the numerical evaluation.The two-loops calculations need a high-performance computing facility which is tailored to next-to-next order calculations in low-energy electroweak physics, to be established at the Grenfell Campus of Memorial University in 2016.

3.5.2.6 Understanding the fundamental properties of nucleons and of nuclei through electromagnetic and electroweak interactions

In the electromagnetic sector, calculations of two-photon exchange (TPE) radiative corrections have been instrumental in resolving the discrepancy between measurements of electron-nucleon scattering form factors using Rosenbluth and polarization-transfer techniques, in making progress in understanding the proton radius problem, and in the interpretation of other precision measurements in electron scattering. Low-energy experiments in atomic parity-violation and in parity-violating electron-proton scattering are a vital complement to direct tests of the Standard Model. These measurements have the potential to give constraints on new physics, provided that the critical hadronic radiative corrections are understood. A major component of the theoretical research based at the University of Manitoba is aimed at unravelling these hadronic contributions and their associated uncertainties through the use of dispersion relations based on data, covering both the deep-inelastic regime as well as nucleon resonances. For example, the NLO effects in parity-violating electron scattering have been calculated with monopole form factors for the hadronic currents, and so have corrections to the weak charge of the proton due to the gamma-Z box term [A. Sibirtsev *et al.*, Phys. Rev. D 82, 013011 (2010)].

3.5.2.7 Nuclear reaction studies and structure of nuclei including continuum effects

Weakly bound or even unbound exotic nuclei produced at rare isotopes facilities like TRIUMF can only be understood using methods that unify the description of both bound and unbound states. Using state-of-the-art no-core shell model with continuum (NCSMC) methods, not only can predictions of the ground-state observables of light nuclei be made, but resonances and cross sections of nuclear reactions can be calculated.

Recently significant progress has been made in the development and implementation of the NCSMC [S. Baroni *et al.*, Phys. Rev. Lett. 110, 022505 (2013); S. Baroni *et al.*, Phys. Rev. C 87, 034326 (2013)] and a first demonstrations produced of its power in the investigation of resonances of the exotic ^{7}He nucleus. Further, the TRIUMF theory group has developed a new capability to include chiral three-nucleon (3N) interactions in the NCSMC [G. Hupin *et al.*, Phys. Rev. C 88, 054622 (2013); J. Langhammer et al., Phys. Rev. C 91, 021301(R) (2015)]. This allowed the study of continuum and 3N effects in the structure of ^{9}Be. Further, it enabled the first accurate *ab initio* calculations of proton-^{4}He scattering in the resonance region, see Figure 3.49 and Ref. [G. Hupin *et al.*, Phys. Rev. C 90, 061601(R) (2014)]. It is also now possible to successfully describe in a unified way the structure of ^{6}Li and cross sections of deuteron-^{4}He scattering and shed the light on the unresolved issue of the asymptotic $D-$ to $S-$wave ratio in the ^{6}Li ground state wave function [G. Hupin et al., Phys. Rev. Lett. 114, 212502 (2015)]. In parallel with these developments the nuclear reaction theory has been generalized to include three-body clusters, such as ^{4}He-n-n [S. Quaglioni *et al.*, Phys. Rev. C 88, 034320 (2013)]. This work resulted in the first *ab initio* study of resonances of the Borromean ^{6}He nucleus [C. Romero-Redondo *et al.*, Phys. Rev. Lett. 113, 032503 (2014)].

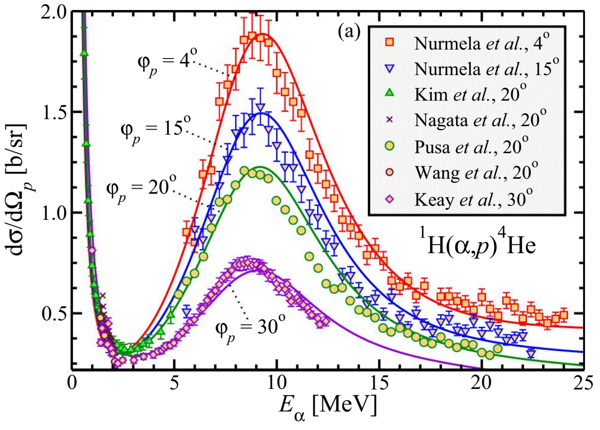


Figure 3.49: Computed (lines) ^{1}H(^{4}He,p)^{4}He angular differential cross section as a function of the incident ^{4}He energy compared with data (symbols).

New developments of *ab initio* reaction theory have opened a new avenue to investigate the role of 3N forces in proton elastic scattering differential cross sections. The TRIUMF theory group are investigating resonances of the exotic unbound ^{11}N nucleus as a proton+^{10}C system, which can be measured experimentally at the IRIS facility at TRIUMF-ISAC. The calculated cross sections compare well in magnitude with the measured one. The magnitude and shape of the measured angular distribution shows the first signature of 3N forces in scattering cross sections. In a related study under way the mirror of ^{11}N, the halo nucleus ^{11}Be, is now under investigation.

The long-term plans for these theoretical frameworks include the development of the NCSMC with the three-body cluster towards the ultimate goal to calculate properties of the exotic Borromean nucleus ^{11}Li, which has been a focus of many experimental studies at TRIUMF. Further, a focus will be made in reaction theory calculations of transfer reactions such as (d,p), (d,n) and (p,t) frequently used in TRIUMF experiments. As the NCSMC approach with χEFT forces is capable of providing realistic many-nucleon wave functions of both bound and unbound states with proper asymptotic behaviour, a significant effort will be made in investigations of electroweak processes in nuclei. Immediate examples include the $E1$ transitions between halo states and photodisintegration of ^{11}Be, calculations of (p,γ), (α,γ) and (n,γ) capture reactions relevant for nuclear astrophysics, as well as weak decays relevant to investigations of fundamental symmetries such as the ^{6}He beta decay that is being measured with high precision at present. The ultimate goal for the next five years is to study alpha clustering, e.g., in ^{12}C and ^{16}O, and reactions involving ^{4}He, e.g., $^{8}\mathrm{Be}(\alpha,\gamma)^{12}\mathrm{C}$, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$.

By combining the Lorentz integral transform method and the many-body coupled-cluster theory, the TRIUMF theory group have recently developed a brand new method, named LIT-CCSD to tackle electromagnetic breakup reactions in the medium mass regime. First successful applications of the method have addressed the photo-absorption of oxygen isotopes [S. Bacca *et al.*, Phys. Rev. Lett. 111, 122502 (2013)] and calcium isotopes [S. Bacca *et al.*, Phys. Rev. C 90, 064619 (2014)]. The results on the neutron-rich ^{22}O isotopes are shown in Figure 3.50 and nicely explain the low-energy soft-dipole mode measured at GSI.

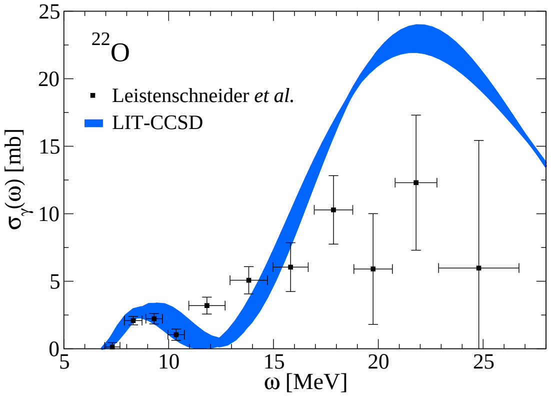


Figure 3.50: Theoretical calculation (band) of the ^{22}O dipole cross section as a function of the photon energy compared to experimental data by Leistenschneider et al., taken at GSI (Germany).

These studies will make it possible to address the open question to whether the soft dipole resonance in neutron-rich nuclei, arising from an oscillation of the halo neutrons and the core, can be well described. In the future it is planned to extend the LIT-CCSD theory to open-shell nuclei, starting from ±1 nucleon outside of the closed shell. The first physics case that will be addressed is the isoscalar dipole resonance of ^{11}Li, recently observed at 1.03(03)MeV from the deuteron inelastic scattering [R. Kanungo *et al.*, Phys. Rev. Letts. 114, 192502 (2015)] measured at the IRIS facility at TRIUMF and described as a research highlight in Sec. 1.2.3.

Furthermore, improvements to the theoretical tools are envisioned by going beyond the presently adopted approximation schemed named CCSD, i.e. coupled cluster with single-double excitations. The first step is to introduce triple corrections in the excited states, to assess solid error bars in the calculations. Future applications will include magnetic and Gamow-Teller transitions in ^{48}Ca.

Progress in the inclusion of 3N forces was recently made using a newly developed χEFT force named N2LOopt [Ekstrom *et al.*, Phys. Rev. C 91, 051301(R) (2015)], which is very soft and allows a fast convergence. The electric dipole polarizability and the weak charge form factor of ^{48}Ca are presently being calculated. The latter will be crucial to support the parity violating electron scattering experiment CREX at JLab, where Canadian colleagues at the University of Manitoba are involved. Finally, on the long term, one would like to apply coupled-cluster theory to the study of neutrino-nucleus interactions. Neutrino cross sections and nuclear effects lead to systematic uncertainty in the extraction of oscillation parameters in neutrino experiments, such as T2K. In fact, neutrino detectors do not usually consist of pure hydrogen, but involve more complex nuclei. Presently, the data analysis of neutrino experiments is systematically limited by simple nuclear models, such as the relativistic Fermi gas, for the interaction of neutrinos with the nuclei in the detectors. Ab initio calculations of neutrino-nucleus cross sections with quantified uncertainties are called for by the neutrino community and can be tackled with methods developed at TRIUMF.

3.5.2.8 Evolution of nuclear shell structure

Understanding and predicting the formation of shell structure in exotic nuclei is a central challenge for nuclear theory. Atomic mass measurements performed at TRIUMF and ISOLDE of the very neutron-rich Ca and K isotopes greatly help revealing detailed information of the effective interaction of nucleons, by providing access to the nuclear binding energies. The experimental results found for ^{52}Ca deviated by almost 2 MeV from the previous measurements but agree well with the predictions from modern theory [J. D. Holt et al., J. Phys. G 39, 085111 (2012)] where 3N forces were included. The new ^{53,54}Ca masses are also in excellent agreement with modern theoretical predictions (Fig. 3.10) and unambiguously establish $N = 32$ as a shell closure [F. Wienholtz *et al.*, Nature 498, 346 (2013)].

A novel *ab initio* method, the in-medium similarity renormalization group (IM-SRG), is now being developed for open-shell nuclei, which provides the first non-perturbative calculations of valence-space Hamiltonians. Very promising first results have been obtained in oxygen [S. K. Bogner *et al.*, Phys. Rev. Lett. 113, 142501 (2014)], where spectroscopy of very neutron-rich isotopes was of similar quality to the best phenomenological models. In addition, increasing the number of valence protons to the F and Ne isotopes finds the same level of excellent agreement with experiment.

Another approach to medium-mass nuclei pursued by Canadian researchers is the Self-Consistent Green's Function (SCGF) method and its variants. It has been successfully applied to oxygen, fluorine, and nitrogen isotopic chains [A. Cipollone *et al.*, Phys. Rev. Lett. 111, 062501 (2013)] as well as to open shell nuclei in the calcium region [V. Soma *et al.*, Phys. Rev. C 89, 061301 (2014); M. Rosenbusch *et al.*, Phys. Rev. Lett. 114, 202501 (2015)]. The Canadian contribution primarily focuses on the chiral nucleon-nucleon and three-nucleon interaction input to these calculations. The goal is to extend the applicability of these approaches to Ni isotopes and beyond.

3.5.2.9 Theoretical nuclear astrophysics

Certain reactions important for light element astrophysics, such as $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$, $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$, or the holy grail of astrophysics, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, are hard or impossible to measure at the astrophysically relevant energies at which they occur in the stellar environment (the Gamow window). These measurements are typically performed at higher energies and then extrapolated down to the energy of interest. Predictive first-principles nuclear theory of these reactions is therefore essential. Even if low energy measurements are achievable in underground laboratories such as the Laboratory for Underground Nuclear Astrophysics (LUNA) in Italy or the Sanford Underground Research Facility (SURF) in South Dakota, the beam-target experiments suffer from electron screening which is absent in the stellar environment. Then the predictive nuclear theory becomes indispensable to extract the correct physics.

At TRIUMF, the theory group is developing a unified approach to nuclear structure and reactions, the no-core shell model with continuum (NCSMC), capable of simultaneous description of bound- and unbound states from the first principles, i.e., from accurate nucleon-nucleon and three-nucleon interactions derived within the chiral effective field theory (χEFT). An example of recent (and first ever *ab-initio*) calculations within this approach include the $^{3}\mathrm{He}(d,p)^{4}\mathrm{He}$ fusion reaction relevant for primordial nucleosynthesis and the $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ capture reaction important for the solar neutrino physics and the Solar Model. Ongoing efforts include *ab-initio* calculations of the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ reaction. These results can be compared directly to a recent DRAGON measurement.

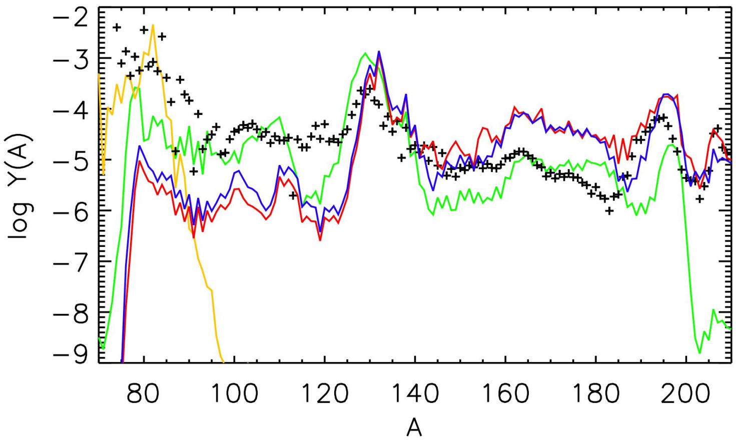


Figure 3.51: Final abundances for r-process nucleosynthesis in accretion disks. The yellow line ignores general relativistic effects while all other lines include different effects. The green line ignores matter rotation and black hole spin, the blue line includes matter rotation and the red line takes into account matter rotation and black hole spin.

Also being investigated is the $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$ reaction, which is the strongest neutron poison in the *s*-process. This reaction has been measured with the activation technique combined with the detection of long-lived $^{14}\mathrm{C}$ via accelerator mass spectrometry [A. Wallner *et al.*, in prep. for Phys. Rev. C]. Since the statistical model cannot be applied for light isotopes, *ab-initio* calculations can help for these cases.

Researchers at the nuclear theory group at the University of Guelph study the influence that neutrinos have on astrophysical phenomena occurring under the extreme matter conditions present in supernovae, neutron star mergers and black hole accretion disks. Neutrino emission, important itself among others for its possible detection at facilities, e.g. SNOLAB and SuperKamiokande, is an integral part of the understanding of the synthesis of elements. Neutrinos set the electron fraction of the medium, via weak reactions with neutrons and protons, determining the kind of nuclei processed in outflowing matter around these stellar objects. The neutrino spectra can be affected by neutrino oscillations, strong gravitational fields and the equation of state (EoS) of nuclear matter. This influence can be seen in the final abundances for r-process nucleosynthesis, see Fig. 3.51 [O. L. Caballero *et al.*, Astrophys. J. 745, 170 (2012)]. On the other hand, the nuclear matter EoS can strongly affect the gravitational waves and the neutrinos emitted from neutron star mergers [C. Palenzuela *et al.*, Phys. Rev. D 92, 044045 (2015)].

3.5.3 The next five years and beyond

Owing to its very nature, theoretical research depends somewhat less on material infrastructure that requires long-term advance planning than its experimental counterpart. However, the future trends in theory can be extracted with confidence from the items presented in this section, some of which already contain an overview of things to come. It is therefore clear that advances in experimental nuclear physics will be accompanied by comparable progress in theory. In addition to the many Canadian experimental endeavours receiving theoretical support, theorists – during the coming years and beyond – will continue their association with major foreign laboratories such as GSI/ FAIR, RIKEN, NSCL/FRIB, JLab, the LHC, and RHIC. Our community will continue to make significant contributions in all the major areas that define modern nuclear theory, in the time period relevant for this report:

Lattice QCD and non-perturbative approaches Lattice QCD provides a first-principles method to explore the possibility of bound states other than the standard set of hadrons. For instance, recent experiments report results for new states near the charmonium and bottomonium thresholds that may involve tetraquarks or some similar states. Lattice QCD has the potential to study those scenarios and to interpret the underlying physics. In this context and in the short- and medium-term, new lattice methods will continue to be refined in the context of conventional bottom-quark hadrons that could prove useful for lattice QCD studies of unconventional bound states. In the finite temperature and baryon density domain, new techniques will be perfected to extend calculations of the QCD equation of state to higher densities, where the QCD action acquires an imaginary value that challenges the probabilistic nature of lattice calculations. Canadians are also actively pursuing efforts to obtain a gravity dual to QCD, thereby enabling the use of string theory techniques to perform analytical, strong-coupled field theory calculations of quantities with experimental relevance.

Perturbative QCD Much of our current knowledge of the substructure of hadrons is based on perturbative QCD, the foundation of which is factorization: the ability to theoretical separate short- and long-distance physics, and to therefore deal with them separately. In the coming years, cross section measurements, paired with precise calculations up to high perturbative order – with the implied sophisticated technology – will continue to be a necessary requirement for obtaining a precise map of the hadronic substructure, including that of the transition region between microscopic and emergent degrees of freedom. Those developments will include the creation of sophisticated numerical tools for the automatic computation of high-order amplitudes.

Effective field theory (EFT) EFTs are a powerful tool in cases where the physics at hand requires a separation of energy scales. This turns out to be the case in QCD, where the long distance phenomena are described in terms of non-perturbative hadrons, and the short-distance physics is formulated in terms of partons. At energies below the proton mass, chiral effective theory incorporates the spontaneous breaking of QCD's chiral symmetry. It has successfully been applied to mesons for some time, and recent breakthroughs have occurred in its use in few-nucleon systems. Canadians theorists will therefore continue to test this theory by performing studies in light- and medium-mass nuclei, in a continuing fruitful dialogue with their experimentalist colleagues. Concrete future plans for calculations involving the NCSMC (using χEFT) include the evaluation of (p, γ), (α, γ) and (n, γ) capture reactions in light nuclei that are relevant for astrophysics. The ultimate goal for the next five years in that field is to study reactions involving ^{4}He, e.g ., ^{8}Be$(\alpha, \gamma)^{12}$C, ^{12}C$(\alpha, \gamma)^{16}$O, as well as the neutron source reaction ^{13}C$(\alpha, n)^{16}$O relevant for the s-process.

Phenomenology and model-building The development of phenomenological approaches guided by empirical data are an essential step that often pave to way to the development of more fundamental theories. They not only serve to guide intuition, but therefore fill the gap that often exists between first-principles approaches and experimental measurements. This category encompasses a large variety of different models and techniques that have been very successfully used by Canadians researchers. Good examples of continuing work are the cross-comparison of results from chiral perturbation theory with lattice calculations, potential model predictions of hadronic mass spectra, and the development of geometries in weakly-coupled gravity that translate to QCD-like field theories under a duality transformation.

3.5.4 Summary

It is essential to maintain a diverse program of research in theoretical nuclear and hadronic physics. A large portion of this theoretical work demands the features associated with HPC facilities; these aspects are discussed in section 4.4 of this document. In addition, much of the progress in theory research is linked to the mentoring of the next generation of theorists. A great opportunity therefore exists to further strengthen and grow this program with strategic investment into highly-qualified personnel who can accelerate the efforts of the recognized Canadian world leaders at the forefront of an exciting and fast-moving discipline that is intimately linked to Canadian experimental efforts in nuclear physics.

Chapter 4

Opportunities Enabled by New Facilities

4.1 Canadian facilities

4.1.1 TRIUMF

4.1.1.1 The national and international roles of TRIUMF

As evident throughout this report, TRIUMF is an important resource for many parts of the Canadian nuclear physics program. A large fraction of Canadian nuclear physicists use TRIUMF as their primary experimental facility, and as such rely heavily upon TRIUMF's capability to develop and deliver both high-quality and high-intensity beams. Because of the favourable and unique characteristics of the rare ion beams in particular, TRIUMF is host to over 500 scientist and student researcher visits per year and has more than 50 international agreements and partnerships. Furthermore, a major collaboration between Canadian and Japanese partners will result in a world-leading ultra-cold neutron source at TRIUMF in 2017. The continued development and delivery of high-quality beams is clearly a very high priority item of the TRIUMF 5 Year Plan, and will be of great benefit to the nuclear structure, nuclear astrophysics and fundamental symmetries programs outlined in this report.

Moreover, TRIUMF also plays a major role as a national infrastructure support base to the offshore portion of the Canadian nuclear physics program. 86% of Canada's subatomic physics research involves TRIUMF in some manner. A noteworthy example is the support for the Qweak experiment at JLab. The total NSERC support for the project was \$3.4 M, with \$0.7M towards construction of key elements of the hardware, including fabrication of the water-cooled copper conducting coils and holders for the Qweak spectrometer, development and instrumentation of a novel diamond microstrip detector for the Hall C Compton polarimeter, and a small quartz scanning detector used to map the event distribution across the Qweak main detector bars. TRIUMF provided crucial infrastructure support to the Qweak experiment, including oversight of the spectrometer coil fabrication, and design and construction of all of the low-noise analog electronics that were used to read out the Qweak main detectors and auxiliary current mode instrumentation.

TRIUMF's continued role as a base of national infrastructure support, in addition to its role as the host of a vibrant in-house nuclear physics program, must be maintained with very high priority.

4.1.1.2 The Advanced Rare IsotopE Laboratory – ARIEL

Until now, TRIUMF's rare isotope beams have made use of the Isotope Separation On Line (ISOL) production technique of proton spallation of a thick target. This technique has the advantage of producing very intense beams of certain radioactive species, but as the production mechanism depends on the free-atom chemistry of the element to be studied, there are certain beams which cannot easily be produced in this manner. Thus, ISOL facilities such as TRIUMF's are complementary to those using in-flight fragmentation techniques, such as FRIB, RIBF, and GSI.

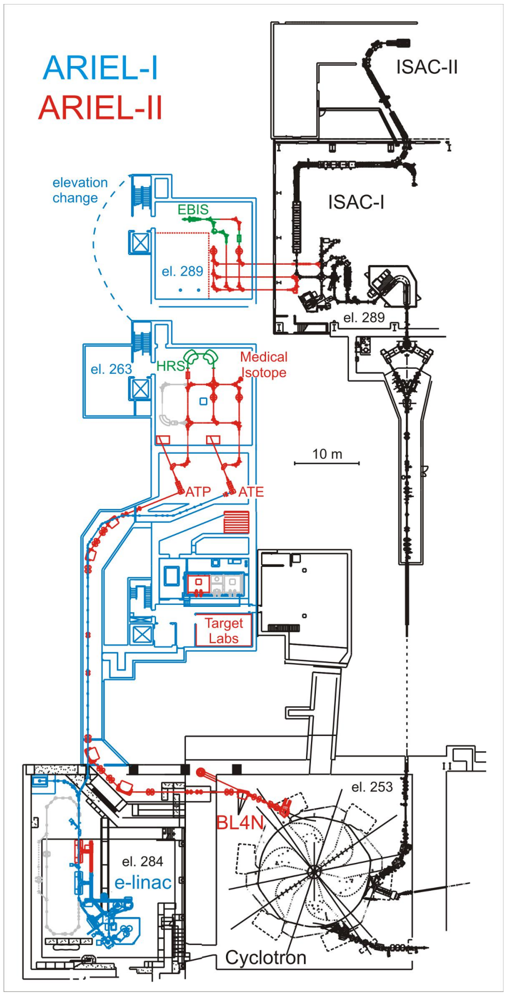


Figure 4.1: Schematic layout of ARIEL at TRIUMF.

TRIUMF has recently completed ARIEL-I, with the goal to significantly expand TRIUMF's Rare Isotope Beam (RIB) program for nuclear physics. After the completion of ARIEL-II, ARIEL will consist of a electron accelerator (eLINAC) with energies > 30 MeV at a power of > 100 kW for isotope production via photo-fission, as well as a second proton beam line from TRIUMF's 500 MeV cyclotron for isotope production via proton-induced spallation and fission. The ARIEL facility, with its dramatic increase in RIB availability and further reach to the extremes of isospin, will be of very clear benefit to the Canadian nuclear physics research program.

Over the next five years, ARIEL will move from construction to delivering science in a phased approach that brings new capabilities online as early as possible. The five project phases are planned as follows:

Phase 1: Implement the target station for the eLINAC and the required RIB transport beam lines to deliver beam to ISAC-I.

- Start materials science with β-NMR and beams for fundamental symmetries (^{8}Li) and nuclear astrophysics (^{10,11}C).
- Dates: 2014-2018

Phase 2: Implement nuclear ventilation, the laser ion source, the actinide radio-chemistry lab, and the safety systems to utilize the actinide target for photo-fission.

- Start photo-fission of uranium from the eLINAC to reach the r-process path.
- Dates: Laser room and labs, 2015-16. Photo-fission, 2018-20.

Phase 3: Implement RIB transport beam lines to support the CANREB project deliverables, including the HRS and the EBIS-based charge breeder system. Implement the medical isotope collection station at the HRS.

- Begin purified accelerated high mass beams (CANREB), and medical isotope production.
- Dates: 2016-20.

Phase 4: Implement the proton target station and the required RIB transport beam lines to connect to those constructed in Phases 1,3. Construct the BL4N proton driver beam line to the target station.

- Begin the fundamental symmetries program with the new proton beamline "beamline 4 North" (BL4N).
- Dates: 2015-21.

Phase 5: Possible upgrade of the eLINAC driver to higher energies and higher power.

- Extension of the photo-fission program with higher power.
- Dates: not yet determined.

Note that the dates are preliminary, and will be adjusted as necessary to match resource availability.

For a full exploitation of the ARIEL/ISAC science capabilities, the project grants for the various experimental facilities (DRAGON, EMMA, Fr-Trapping Facility, GPS, GRIFFIN, IRIS, Laser spectroscopy, RnEDM, TIGRESS, TITAN, TRINAT, TUDA) will need to be increased.

The maximal benefits from the ARIEL capabilities will be unlocked when the primary and secondary beam capabilities are fully available. This includes maximal power on target for the electron and the proton beams within the ARIEL framework, as well as full secondary beam (rare beam) optimization. While the actual primary beam production and optimization is well within the TRIUMF operational mandate, the necessary R&D for developing new secondary beam production capabilities, such as the characterization of new target geometries and materials, or new ionization schemes, is driven through NSERC SAP resources. Also, there is a long-standing need for high-intensity beams for key reactions involved in explosive hydrogen and helium burning in stellar explosions. This requires completely new target concepts, e.g. liquid targets, or harvesting of long-lived isotopes, like ^{44}Ti, from irradiated targets. Again, research on this front can only be driven by NSERC funding.

4.1.1.3 Ultra-cold neutron source for fundamental physics

Ultra-cold neutrons (UCN) are free neutrons of such incredibly low energies that they may be stored in material bottles. Hotter neutrons would simply pass through the bottle walls. This property of being able to bottle UCN allows experimenters to study the properties of the neutron with amazing precision, unattainable by any other means.

Experiments using UCN around the globe are limited by the number of neutrons available to the experiment. To advance this field of fundamental neutron physics, a new facility is being built at TRIUMF to deliver more UCN than ever before. It leverages TRIUMF's 500 MeV cyclotron via a unique combination of a spallation neutron source and a superfluid helium UCN converter. With commissioning foreseen in 2017, it will provide high densities of neutrons with energies below around 250 neV, to two experimental ports.

Ultra-cold neutrons are ideally suited to precision experiments testing fundamental symmetries at low energies. The top science priorities in the field are measurements of the neutron electric dipole moment, neutron decay parameters, the neutron lifetime, and gravitational interaction studies. While one experimental port is dedicated to an EDM experiment (Sec. 3.4.2.1), the second port will be opened to the international user community. Proposals for experiments with UCN will be evaluated through the TRIUMF Experimental Evaluation Committee (EEC).

The goal is to create an active international user base exploiting the high-density UCN source at TRIUMF by 2022.

4.1.1.4 Longer-term upgrades

Although ARIEL has not yet been fully implemented, it is time to consider longer-term possibilities for the future facility development of ARIEL. The subatomic physics long range planning exercise provides the ideal opportunity to start this discussion.

Several upgrade options are in very early stages of discussion:

1. Optimize the ISAC multi-user capabilities by adding a second independent acceleration path to ISAC-I (BL4N).

2. Implement a recirculation ring for the eLINAC, with the capability to establish a free electron laser for THz radiation and use of the recirculated beam for operation of the eLINAC as an Energy Recovery LINAC.

3. Expand the ISAC facility, extending the energy range of the ISAC-II SRF linac and feeding beams into a new heavy-ion storage ring for in-ring experiments, such as reaction experiments with recirculating beams. That ring should also have acceleration capabilities (or at least

should be upgradable) for further expansion (e.g. extraction at 150-200 A MeV and secondary fragmentation). The fragmentation of a high-intensity rare isotope beam produced from ARIEL, such as ^{132}Sn, could potentially provide access to very neutron-rich species even beyond the reach of FRIB. Coupling of an intersecting electron storage ring could provide opportunities of electron scattering on short-lived nuclei.

4.1.2 SNOLab

SNOLab has been developed as one of the world's premier underground laboratories through the considerable assistance of CFI, the Governments of Ontario and Canada, and university partners. As discussed in Sec. 3.4, experiments proposed for or under development at SNOLab may be able to address some of the most important questions regarding the nature of the neutrino. The decision by the USA to consider siting a tonne-scale neutrino-less double-beta decay experiment at SNOLab is very exciting, regardless of which experiment is chosen. Particularly if nEXO is selected in the DOE decision-making process, it will allow Canadians to leverage considerable international resources while participating in a world-class experiment onshore. The consultations for SNOLab's institutional long range plan are just getting underway, and this is an excellent opportunity to ensure that the subatomic physics community's long term aspirations and SNOLab's are in alignment.

4.1.3 Nuclear Science Laboratory (NSL) at Simon Fraser University

The Nuclear Science Laboratory (NSL) at Simon Fraser University has acquired a deuterium/tritium neutron generator, a CNSC License to Commission in 2014, and the 8π spectrometer from ISAC. Some experiments planned include detailed spectroscopy of the isotopes involved in the double-beta decay of ^{76}Ge as well as precise measurements of neutron elastic scattering on various targets. It also provides the means to apply nuclear methods for trace isotope analysis of interest to archeology, environmental, earth sciences, forensics, and other areas of research.

4.2 International facilities

4.2.1 The Thomas Jefferson National Accelerator Facility

With the capability to deliver variable energy electron beams between 1-12 GeV of unprecedented quality and stability, Jefferson Lab (JLab) is the world's largest nuclear physics user facility, numbering nearly 1400 users. Several groups of Canadian experimentalists and theorists perform research there, making it the largest center for offshore Canadian nuclear physics research. Canadians are the third largest international group at JLab, behind France and Italy.

The JLab high-luminosity continuous-wave superconducting electron LINAC has just been upgraded from 6 GeV to 12 GeV maximum beam energy, opening up many new physics opportunities that have been rated very high merit by a wide variety of scientific reviews. Canadians have leadership roles in a variety of experiments, including the GlueX, Pion and Kaon Form Factor, Proton Form Factor, PREX/CREX, Qweak, and MOLLER experiments discussed elsewhere in this document. We also note the Dark Light experiment at JLab has significant leadership from scientists from the Perimeter Institute, which is searching for a low mass sterile photon as a dark matter candidate.

Over the past decade, there has been a significant effort by Canadians to contribute to new hardware in Halls A,C, and D, and this equipment is either already in the process of being commissioned with beam, or will be expected to in the next 1-2 years. Slightly further in the future will be the MOLLER experiment, with construction expected to start in 2017 and data taking in 2021-23. The timescale for the proposed SoLID large acceptance, high luminosity detector is 1-2 years later than MOLLER. In all of these cases, Canadians have very visible roles. These investments are very effective, not only in terms of scientific output, but also in terms of leveraging international investments to best advantage.

Canadian contributions to the JLab 6 GeV program have shown themselves to be of very high impact, and this leadership has been even more visible in the highest priority parts of JLab's 12 GeV program. In order to capitalize on this leadership and the noteworthy scientific opportunities, these Canadian efforts should be supported with high priority.

4.2.2 CERN (Antiproton Decelerator)

The ALPHA–Canada collaboration draws upon Canadian expertise in atom, laser, microwave and trap techniques that are common to other CINP projects, such as the TITAN, CPT, TRINAT, FrPNC, and UCN experiments. ALPHA–Canada is the single largest group in ALPHA, consisting of about 1/3 of the international collaboration. The Canadian contributions to the ALPHA program are very significant, and they have leading scientific and technical impact within the collaboration.

In the 2015 competition, they have received significant CFI funding to help construct the ALPHA-g experiment, whose ultimate goal is to make precision measurements on the gravitational interaction of antimatter and the Earth. More than 80% of the funding for ALPHA-g is expected to come from Canadian sources, including provincial and institutional matching. ALPHA-g will allow ALPHA to double its productivity by simultaneously operating the ALPHA-2 trap for precision spectroscopy and the ALPHA-g trap for gravity. In response to the strong interest by the international antiproton community, CERN is investing significant resources to build the new ELENA facility, an upgrade to the AD ring which will increase antiproton trapping efficiency by up to 2 orders of magnitude, and have the capability to serve 4 simultaneous experiments. ELENA is expected to come online in 2018.

ALPHA represents one of the most successful recent examples of Canadian leadership in subatomic physics, as recognized by national and international awards for its members and students. With the recent investments by CFI, ALPHA-Canada will clearly require a phased expansion of operating funds to make full use of the new opportunities enabled by this equipment.

4.2.3 Smaller initiatives

The Canadian contributions at the facilities listed below are smaller but they nonetheless have significant impact within their respective collaborations. Each are worthy of funding on their own merits. In several cases, the investigators have indicated that their efforts are expected to wind down over the next 5-10 years.

Argonne National Laboratory (ATLAS) The Canadian Penning Trap (CPT) mass spectrometer, originally constructed for use at the TASCC facility of the AECL Chalk River Laboratories, has been operational at Argonne National Laboratory since 2001. Canadian physicists from Manitoba and McGill use this facility. These studies are complementary to those at ISAC as the isotopes are produced via in-flight in reactions as opposed to the target-diffusion, so the radioactive species available at ATLAS are insensitive to chemistry. At present, CPT operates on the low-energy beamline of CARIBU (Californium Radioactive Ion Beam Upgrade), giving access to rare heavy ions not previously available for study anywhere. In the next 1-2 years, the CPT is planned to be moved to a new location where accelerated, high-energy, high intensity beams will be available. The options for continuing this work past this 5-year period are yet to be decided.

Duke University Free-Electron Laser Facility (DFELL) There has been a considerable investment of Canadian infrastructure from the former Saskatchewan Accelerator Laboratory to the High Intensity Gamma Source (HIGS) at the Duke University Free-Electron Laser Facility in North Carolina. A single Canadian principal investigator is involved in experiments at this facility, which are summarized in Sec. 3.1.2.4.

GSI Helmholtz Centre for Heavy Ion Research (GSI) One Canadian researcher is spokesperson of several experiments making use of the fragment separator FRS at GSI as described in Sec. 3.2.2.5. GSI is currently embarking upon a major expansion of its facilities via the international FAIR project, and the Canadian investigator is coordinator of the future continuation of these experiments within the SuperFRS Collaboration.

Japan Proton Accelerator Research Complex (J-PARC) As summarized in Sec. 3.4.2.5 a Canadian group is joining a focused program there to re-measure the muon's anomalous magnetic moment utilizing a new technique.

Mainz Microtron (MAMI) The Mainz Microtron (MAMI) delivers electron beams up to 1.6 GeV energy. Along with a polarized tagged photon beam, frozen-spin target, and large acceptance detectors, the MAMI-A2 facility has unique access to high-precision measurements of nucleon structure. During 2009-2014, as the JLab experimental program was curtailed during 12 GeV upgrade construction, the Canadian research efforts at the Mainz facility grew. Internal discussions at Mainz indicate the MAMI accelerator complex will wind down operations over the next 5-7 years in favour of other opportunities. This dovetails well with the Canadian investigator plans, which are to complete the transition of most of their efforts back to JLab by the end of the decade.

Oak Ridge National Laboratory (SNS) As discussed in Sec. 3.4.2.5, some Canadians are involved in fundamental neutron studies using the Spallation Neutron Source (SNS) at Oak Ridge. This work is expected to gradually ramp down by 2022, as efforts are diverted to the MOLLER experiment at JLab.

Radioactive Ion Beam Facility (RIBF), RIKEN Radioactive ion beam production by in-flight fragmentation complements the ISOL production method at ISAC, and the Canadian γ-ray spectroscopy and nuclear astrophysics community complements its ISOL-based research at TRIUMF with experiments at the RIKEN Nishina center in Japan. The experimental program there is briefly summarized in Secs. 3.2.2.5 and 3.3.2.2.

4.2.4 Electron-Ion Collider (EIC)

The science case for the EIC is briefly presented in Sec. 3.1.3.3. The proposal is to construct the world's first electron-nucleus collider, with the flexibility to change the nuclear ion species as well as the beam energies. For electron-proton collisions, the EIC would be the world's first collider where both beams are polarized. The EIC luminosity is proposed to be 100-1000 times that of the former HERA accelerator at DESY. Without polarized proton beams, HERA could not access the proton's spin structure, and with the much higher luminosity, measurements that would take years at HERA could be done in just a matter of weeks at EIC.

The latest U.S. long range plan for nuclear physics is in the final stages of being finalized, but it is widely expected that NSACs long-range planning group will strongly recommended construction of the EIC. The project has not yet been approved by the DOE, but most projects receiving this level of endorsement have eventually been constructed. Some Canadians are involved in the early planning of the proposed experimental program, and if approved for construction, this interest can easily be expected to grow.

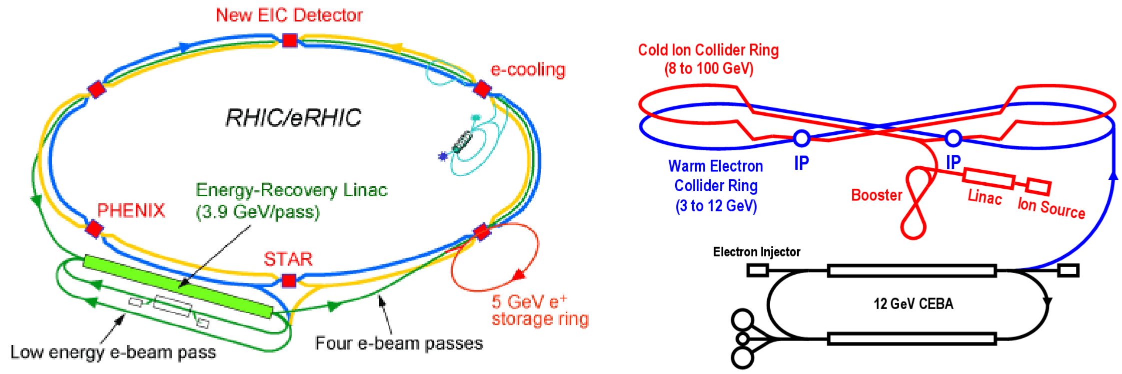


Figure 4.2: Schematic diagrams of the Electron-Ion Collider proposals at Brookhaven National Laboratory and Jefferson Lab.

The EIC would not be built from scratch. The competing proposals from Brookhaven and Jefferson Laboratories are shown schematically in Fig. 4.2. The Brookhaven proposal is to add a 5-10 GeV electron ring inside the existing RHIC tunnel, with a layout that allows subsequent straightforward upgrading to 20-30 GeV. The electrons would collide with heavy ions or protons circulating in one of the existing RHIC accelerator rings. No new civil construction is required, but the accelerator design aspects to achieve the required luminosity are very challenging. The JLab proposal is to add two figure-8 rings, in which the colliding electron and ion beams are stored in two collider rings stacked vertically in the same underground tunnel. The electron ring is made of magnets sourced from the former PEP ring at SLAC, while the superconducting ion ring is new construction. In early 2015, an NSAC subcommittee estimated the cost of both projects to be approximately US$ 1.5 billion. Site selection between the two competing proposals is expected in the next few years, and first physics might be expected to start in the mid-2020's.

4.3 Accelerator development for nuclear physics

The TRIUMF Accelerator Division has plans for projects in several areas of interest to nuclear physicists. Short and intermediate-term projects are primarily in support of enhanced beam properties for ISAC/ARIEL, but longer-term projects include research into new accelerator concepts, such as those discussed in Secs. 4.1.1.4 and 4.2.4. Those projects are directed to beam or accelerator development for a specific goal which would more likely be supported by TRIUMF or CFI funds, while the most fundamental accelerator physics questions might fall within the purview of NSERC SAPES funding.

4.3.1 ISAC/ARIEL development

New target technology One possibility is to investigate new target technology which could lead to new rare ion beams (RIBs) or enhance the yield for existing beams. Proton-induced ion production from a variety of target materials such as SiC, Ta, ZrC, Nb, UC_x has been developed at ISAC and beams from those targets are in routine use. New target materials like carbon nanotubes are being considered that would enhance the diffusion and effusion of the active species with enhanced target lifetimes. Other investigations include two-step targets, where a neutron generator material like tungsten is bombarded by the protons and creates neutrons that fission an actinide target material. The two-step mechanism would provide neutron-rich isotopes in ISAC with less isobaric contamination than from direct spallation.

Target development lab Another possibility is to construct a materials laboratory to study the material properties pertinent to the production of ISOL radioactive beams. The goals would be to gain a better understanding of the complex processes occurring inside the ISOL target, to systematically develop new target materials, and to maximize the rare ion yield. The TRIUMF cyclotron provides the world's highest power ISOL driver at 50 kW. A particular focus of the target development would be to better understand the operation of the targets for the highest beam powers where ISAC could push beyond other facilities in terms of intensity and species.

Rare isotope mining A more practical application is to mine exotic long-lived isotopes from the ISAC proton target station. To date, the spent targets from ISAC are treated as radioactive waste and prepared for disposal. In reality, the targets contain many longer-lived species that would be of scientific interest for nuclear medicine diagnosis and therapy. ARIEL's multi-user capability will enable sufficient beam time for this program. For example, using beams from the new proton beamline (BL4N) and the associated target station, ample amounts of ^{211}Rn can be produced, collected, and extracted for shipment to collaborators. ^{211}At is generated in transit through the decay of ^{211}Rn. TRIUMF plans to focus on demonstrating the production, packaging, and shipment of ^{211}Rn generators (from thorium targets), and explore the radiopharmaceutical production of novel theranostics. Mining the species of interest from the target material will require hot cells, hot chemistry, and significant remote handling capability. In addition to mining the target material, the ISOL process can be used to produce and separate small quantities of rare isotopes from target material for development studies. In this case targets at the end of the run can be heated, products ionized, separated on-line, and deposited in a collection station.

Other project possibilities include the development of an ECR source that can withstand the harsh conditions of the target environment, and to develop new target modules based on the ISAC experience as well as incorporating new ideas from the ARIEL development. Many projects are also planned to extend the ARIEL capabilities beyond those already funded by CFI. These include the construction of two target conditioning stations (for proton and electron targets), a laser ion source to ionize the rare isotopes produced in the ARIEL east station, new hot cells, a medium resolution spectrometer to allow the delivery of higher mass beams, and a conventional chemistry lab.

4.3.2 Longer-term developments

TARIF (TRIUMF Accelerated RIBs for Ion Fragmentation) A new large scale proposal where neutron-rich RIBs of high intensity from ISAC or ARIEL are accelerated in ISAC-II and injected in a new booster linac or synchrotron and accelerated to fragmentation energies. The goal is to reach RIB isotopes further out on the neutron rich side than can be reached with ISOL or standard fragmentation.

TCR (TRIUMF Cooler Ring) A cooler ring could be added either to take the ISAC-II beam directly or after fragmentation. The ring would provide a capability for experiments with stored secondary beams that is unique in the world. The envisaged physics program includes investigations of nuclear ground-state properties and reaction studies of astrophysical relevance, and investigations with highly-charged ions and pure isomeric beams. TCR might also be employed for removal of isobaric contaminants from stored ion beams and for systematic studies within the neutrino beam program. In addition to experiments performed using beams recirculating within the ring, cooled beams can also be extracted and exploited by external spectrometers for high-precision measurements.

Cyclotron intensity upgrade To support the new ARIEL proton line (BL4N), the cyclotron beam intensity must be ramped from the present 300 μA to 400 μA. An upgrade to the H^- source would improve the beam brightness. Beam studies and new centre region hardware are required to deal with the enhanced space charge. A high power beam dump in close proximity to the cyclotron is also proposed that would serve both for high intensity development and isotope production.

Electron-Ion Collider Finally, the US long range plan calls for the construction of an Electron-Ion Collider (EIC) as summarized elsewhere in this document. In kind contributions from TRIUMF accelerator physicists and engineers could be foreseen to support this construction, with the goal to give Canadian scientists a place at the table while engaging in a cutting edge accelerator project.

4.3.3 Broader R&D initiatives

Superconducting Radio Frequency Center The current generation of linacs is enabled by the technology of superconducting radio frequency (SRF) accelerating cavities made of pure niobium. Increased Q values for low energy continuous wave (CW) machines, such as the ARIEL e-LINAC, could lead to dramatic cost reductions. SRF technology transfer from TRIUMF to PAVAC Industries gives TRIUMF a competitive edge to explore new SRF strategies. In order to fully leverage the SRF investment, the SRF infrastructure could be expanded to allow a broader scope of collaboration. Additions include an enlarged clean room, a high vacuum furnace, and a new chemistry lab. This would allow the development of full cryomodule production to support in house projects as well as to allow TRIUMF/PAVAC to participate in large global projects. In particular, components for the front end of a high intensity proton linac would be developed that would have application as a replacement for the 500 MeV cyclotron. This machine would not only support ISAC/ARIEL proton driver requirements but also could be used for neutron production, proton therapy and slow muon production for material science.

Energy Recovery LINAC (ERL) The ARIEL e-LINAC has been installed consistent with adding a single pass recirculating ring to allow the linac to run in Energy Recovery LINAC (ERL) mode or Recirculating LINAC Acceleration mode (RLA). In one case, the electrons are fed back through the acceleration section in anti-phase with the accelerating fields so that the energy gain (beam loading) on the first pass is compensated in the second pass through energy loss and hence energy recovery. ERL offers two important properties: an electron beam having high-brightness and high-power capabilities simultaneously. Thus, ERLs hold the promise of becoming the future backbone of modern accelerator facilities, including the proposed EIC. For ERLs, the demands placed on the electron source, the SRF linac, and the beam transport are severe due to the required beam quality, high current and the CW operation. Ultimately, the technology and concepts have to be put to the test in an ERL test facility. The ARIEL e-LINAC gives TRIUMF most of the required infrastructure to develop an ERL test facility. In addition, a small user facility can be installed by adding an Infrared Free Electron Laser (IR-FEL) on the back straight as a light source.

Accelerator physics education For the last several years TRIUMF has organized an accelerator physics course offered through UBC and the University of Victoria. Ten graduate students are presently registered in accelerator physics projects at TRIUMF and this number is growing as more students and associated universities see the benefit of the expertise and infrastructure at TRIUMF for the training of HQP. It is proposed to grow the program with the addition of key hardware to form an accelerator study centre. The infrastructure would include a small, student-designed cyclotron, a small electron ring, a diagnostic test facility, and an ion source test stand with an analyzing station.

4.4 The role of high performance computing

Funded via CFI, Compute Canada provides shared national computing infrastructure to the nuclear physics research community. This section summarizes the importance of Compute Canada resources to the nuclear physics research community.

4.4.1 Experimental nuclear physics requirements

Jefferson Lab The experiment with the most significant computing demands is GlueX at JLab, which is scheduled to receive its first “physics-quality” beam in the spring of 2016. The GlueX computing model is for the primary data to be permanently stored at JLab and first level processing on those data to be performed there. Monte Carlo simulations and analysis will be performed off-site, with approximately 30% of the simulations to be performed at Canadian facilities. For the Canadian fraction of the simulations, an average demand of 1500 Intel cores (i7 at 2 GHz) is projected for 5 years starting in 2016, with a typical usage pattern of one large job cluster of several million CPU hours, several times per year, and 300 TB of grid-accessible storage starting in 2016, increasing to twice that by 2018.

The MOLLER experiment at JLab, whose data taking is projected to be from 2021-23, plus an additional 4 years of data analysis afterward, and experiments in Hall C of deep exclusive electron scattering reactions starting in 2016 both require Compute Canada resources to run large simulations and perform data analysis. Once MOLLER data taking starts in 2021, storage needs are projected to increase from 200 TB to 2 PB.

TRIUMF The GRIFFIN array at TRIUMF has been designed to perform experiments using radioactive beams, which are produced at ISAC with intensities from 0.01 particles per second to 10^8 particles per second. In the former case, the data collection rates will be small due to the low intensity of the rare isotope beam and typically a few TB per year. In the latter case, with high-intensity rare isotope beams the important physics is often revealed in the observation of very weak gamma-ray transitions from excited nuclear states, which have a relative intensity 5 orders of magnitude lower than the strongest decay branch. The study of these very weak transitions necessitates a very high throughput data acquisition to collect very high-statistics datasets, followed by intensive analysis to identify specific coincidence events. In order to limit the collected data to only the most useful coincidences, the data is filtered for various detector multiplicity and temporal coincidence conditions in real time before being stored on disk. Despite this real-time filtering of the detector signals, the GRIFFIN data acquisition system is capable of writing filtered data at a rate of 300 MB per second and will therefore collect datasets of around 250 TB in typical one-week experimental runs. It is anticipated to perform an average of two of these high-rate runs per year and accumulate 500 TB of new data per year, which will be stored for a minimum of five years while the analysis is completed.

The TIGRESS spectrometer at TRIUMF is utilized in a diverse scientific program in nuclear structure and nuclear astrophysics research. It consists of up to sixteen highly segmented hyper-pure germanium clover detectors, which surround a reaction target where a nuclear reaction is induced by the accelerated radioactive beam from ISAC-II. Charged particles and heavy ions following the reaction are detected in various ancillary detector systems located inside the vacuum chamber at the same time as emitted gamma rays are detected in the TIGRESS detectors. Coincidence triggering conditions between detector sub-systems can be made very selective with such a setup, and due to the typically low intensity of accelerated radioactive ion beams the number of individual events recorded is not as large as in the high-rate decay spectroscopy experiments with GRIFFIN. However, in order to make full use of the position sensitivity of these highly segmented TIGRESS clover detectors it is common to record a short waveform sample from the detector along with the other event data, which is processed in the offline analysis. This waveform collection can increase dramatically the size of the recorded dataset. The TIGRESS digital data acquisition system was custom designed and built as part of the original installation. The full digital data acquisition system is currently being upgraded with the more modern digitizers developed for the GRIFFIN project. Once this new DAQ system is in place, the expected data collection rate will be typically 100 TB per year. The data will be stored for a minimum of five years while the analysis is completed.

4.4.2 Theoretical nuclear physics requirements

There has been a renaissance in the techniques of theoretical nuclear physics, where high performance computing has allowed the investigation of many complex problems that previously had to be treated with more approximate techniques.

Ab-initio nuclear structure This TRIUMF-based project involves large-scale *ab-initio* nuclear structure and nuclear reaction calculations, using as input modern two- and three-nucleon forces derived within chiral effective field theory. Using these forces, the quantum many-nucleon problem is solved for bound and unbound eigenstates. At present, the calculations are performed with the parallel computers at Lawrence Livermore (LLNL) and Oak Ridge (ORNL) national laboratories in the USA, but the computations are expected to transition to Canadian facilities in the future. The computing allocation at ORNL is about 20 million core hours per year, and the calculations use up to 6000 nodes (96000 cores). On the LLNL machines, 128 nodes (2048 cores) are typically used, with CPU usage exceeding a million core hours per year. The computing needs will grow in the future, as calculations are performed for heavier nuclei (sd-shell and beyond). Longer-term, alpha-clustering including the scattering and reactions of alpha-particles with nuclei will be calculated. These problems will require a significant increase of computing power, i.e. by a factor of 10 or more.

Lattice QCD This is a computational method to obtain a quantitative understanding of strong interactions. Even though QCD is the fundamental interaction governing nuclear physics, little is known about their direct connections and only few ab initio calculations exist. In the past the immense complexity of even the simplest nuclei in terms of quarks and antiquarks was an insurmountable obstacle to lattice calculations. However, recent theoretical developments and increase in computing power have made it possible to compute nuclei up to helium on realistic lattice setups. Pushing these boundaries further and determining the spectrum of light nuclei will give a solid foundation in QCD to nuclear physics. The Canadian lattice QCD effort is centered at York University. Primary resources have included a dedicated cluster of 320 cores at York University and CPU/GPU facilities at the Danish Centre for Scientific Computing. Because the lattice effort at York University is growing and the local dedicated cluster is aging, significant growth in the use of Compute Canada resources, of the order of 4500 core-years of CPU and 100 TB of storage, is anticipated.

Quantum Monte Carlo simulations of neutron stars and nuclei The Guelph theoretical group uses a variety of microscopic ab-initio simulation methods to compute the properties of neutron stars and light nuclei. For dilute neutron matter (s-wave interactions), the method of choice is diffusion Monte Carlo (DMC). For more complicated nuclear interactions, nuclear Green's Function Monte Carlo (light nuclei) and auxiliary field diffusion Monte Carlo (infinite matter and medium-mass nuclei) are used. All these methods are exact, modulo the fermion-sign problem and can be extended to become effectively variational methods. These methods use as an ansatz a trial wave function, which embeds sufficient physical insights (from few- or many- body theory) as well as variational parameters, which are systematically varied to approach the state of chosen symmetry. The computations are currently performed on SHARCNET clusters, and typically use 100-1000 cores. Over the next 10 years, needs are projected to increase by a factor of 50-100: the biggest issue is the number of particles, N, that can be handled in the simulation. Since the time required scales as N^3, doubling the number of particles takes 8 times more resources. Neutron-star related systems composed of roughly 100 particles are currently being studied but systems of 400-500 would need to be addressed to be truly realistic.

Relativistic quark-gluon plasma When the nuclear temperature exceeds 170 MeV or about 2 trillion kelvin, the quarks and gluons inside hadrons are liberated to form a quark-gluon plasma (QGP). This new state of matter existed in bulk only when the universe was about a microsecond old. The research focus of the McGill nuclear theory group is the investigation of the ultra-relativistic heavy ion collisions in general, and the properties of the QGP in particular. The computational challenge is to simulate the entire evolution of the ultra-relativistic heavy ion collision, starting from the Lorentz-contracted nuclear initial state, to the QGP phase, and on to the final hadronic state. Each of these steps needs different computing environment: The most CPU-intensive step is the hydrodynamic evolution part, using up to 8 million spatial cells and $\mathcal{O}(10^3)$ time steps, utilizing a parallel computing capability. Another CPU intensive step is the hadronic scattering simulation, where in a typical LHC collision, $\mathcal{O}(10^4)$ hadrons emerge out of the QGP. Keeping track of collisions among these particles is numerically challenging. This part is not parallelized, and requires a massive number of serial nodes since $\mathcal{O}(10^2)$ hadronic simulations need to be performed on each of the $\mathcal{O}(10^3)$ hydrodynamic simulations. Calculations for the outgoing hard and electromagnetic probes have yet different computing needs, requiring a massive storage capability of $\mathcal{O}(10^2)$ TB. It is estimated that at least 2,000 core-years with 3-4 GB/core per year and 250 TB of storage space is required in coming years.

Two-loop effects in precision electroweak measurements A very promising method to search for physics beyond the Standard Model (SM) is to perform high-precision electroweak experiments at the intensity/precision frontier, such as parity-violating Moller scattering, e^+e^- collisions or electron-nucleon scattering. These studies can provide indirect access to physics at multi-TeV scales and play an important complementary role to the LHC research program. These lower-energy experiments tend to be less expensive than experiments at the high-energy colliders, but they are more model-dependent and require significant theoretical input. In order to match the proposed electroweak experimental precision, it is necessary to provide theoretical predictions on the observables of the SM with 1% precision. Since the most of the SM electroweak theoretical predictions employ perturbative expansion in orders of α (fine structure constant), it will be required to consider contributions to the electroweak cross sections of up $\sim \alpha^4$, corresponding to two-loop calculations in the Feynman diagram approach. There has been some success in evaluating higher-order corrections for some specific QED processes, but not much has been done yet for the electroweak sector. Aleksejevs (Memorial) and Barkanova (Acadia) have carried out calculations for a complete set of one-loop electroweak corrections for the e-e scattering and are currently working on two-loop corrections. However, in the case of electroweak processes, full two-loop calculations face dramatic complications due to the presence of massive vector bosons (W and Z) in the two-loop integrals. For the MOLLER experiment at JLab, the calculation of the parity-violating electroweak asymmetries up to the two-loop level requires the computation of thousands of Feynman diagrams. Based on the assumption that a one loop graph analytical result requires around $\sim$5 GB of RAM, about 500 GB of allocated RAM per 100 two-loop graphs are required. Finally, since the first stage of the calculation deals with analytical computations, it is required to store the results permanently, needing of the order of 600 TB of storage. These two-loop calculation techniques can later be adapted for electron-proton processes, electron-positron collisions, and other low-energy experiments involving particles of the SM and new physics.

4.5 Detector development within the Canadian nuclear physics community

The Canadian nuclear physics community has a strong track record of developing innovative detector solutions, and detector R&D is critical to the development of new cutting edge experiments which often have specific geometrical, timing and/or energy resolution specifications. The development of novel detectors for ionizing radiation and the associated readout systems is indeed one of the main drivers of new discoveries, and advances in detector technology have the potential for spin-offs to other fields, such as nuclear medicine and the resource sector. The subatomic physics long range plan is an opportunity to reaffirm the necessity of support for the *design* of detectors for future experiments by leveraging resources at universities and at TRIUMF. Such developments are critical to enable Canadians to continue to be world leaders in the experimental SAP community.

Experiments are designed and built with resources and expertise from Canadian universities and TRIUMF and collaboration with industry. Prior to 2010, funding for detector construction has been provided by NSERC and TRIUMF, and after 2010 by CFI, but the resources and funds for detector R&D have always been fairly limited. In order to meet challenging scientific goals, detector development sometimes must begin at a very early stage of the planning process, requiring early funds for HQP and materials for R&D work. The design, construction and testing of detectors provides unique opportunities for the training of HQP which can often be done at local universities, even if the experiments will run at offshore facilities.

The resources available for detector development and construction at the Canadian universities and TRIUMF are mostly complementary. Universities have key expertise in specific technologies that are critical to the success of particular projects. For example, the University of Alberta has capabilities for machining parts in a low radon environment, the University of Montreal has cutting-edge expertise in readout electronics, and the University of Manitoba has a nearly-completed CFI-funded clean room that will be used to develop detectors for the MOLLER experiment. Such expertise is complemented by the TRIUMF Science Technology Department with its wide ranging expertise for the development of complete detector systems, from conceptual and mechanical design, manufacturing, electronics and data acquisition systems. The TRIUMF resources are available to the Canadian community for projects in which TRIUMF is part of the scientific collaboration, and can provide resources for hire for projects in which TRIUMF is not a collaborator. In addition to the resources of the Science Technology department, projects can rely on specific expertise from TRIUMF's Engineering and Accelerator Divisions.

It is critical to sustain and enhance the capabilities for detector development and construction in the Canadian SAP community. This requires increased coordination and communication within the community, not only on the level of the scientists but also on the level of engineers and technical staff. To enhance this coordination, TRIUMF proposes to initiate a series of topical workshops related to precision machining, detector design, simulations, and integration, as well as readout electronics and data acquisition systems. Such workshops would enable the sharing of technical expertise and would build strong working level connections between institutions at the technical level.

In any funding scenario, the NSERC subatomic physics envelope needs to continue to allow for such long-term directed research and development for the next generation of nuclear and particle physics experiments.

Chapter 5

Demographics, HQP training, and Benefits to Society

In addition to the research into the specific questions outlined in the previous chapters, the Canadian nuclear physics community positively impacts society in a large number of ways and plays a vital role in the training of Highly Qualified Personnel (HQP). Nuclear physicists promote science in general, and nuclear science in particular, to the general public and inspire students to pursue an education in science, specifically nuclear science, applications of which have provided great benefits to society. These benefits include, but are not limited to, the diagnosis and treatment of disease through isotope production, radiation therapies, and detector development applicable to dosimetry in medical as well as space applications. By participating in a project which is technically demanding and contextually fascinating, students have the opportunity to broaden their experience and hone their skills in preparation for the transition to the workforce.

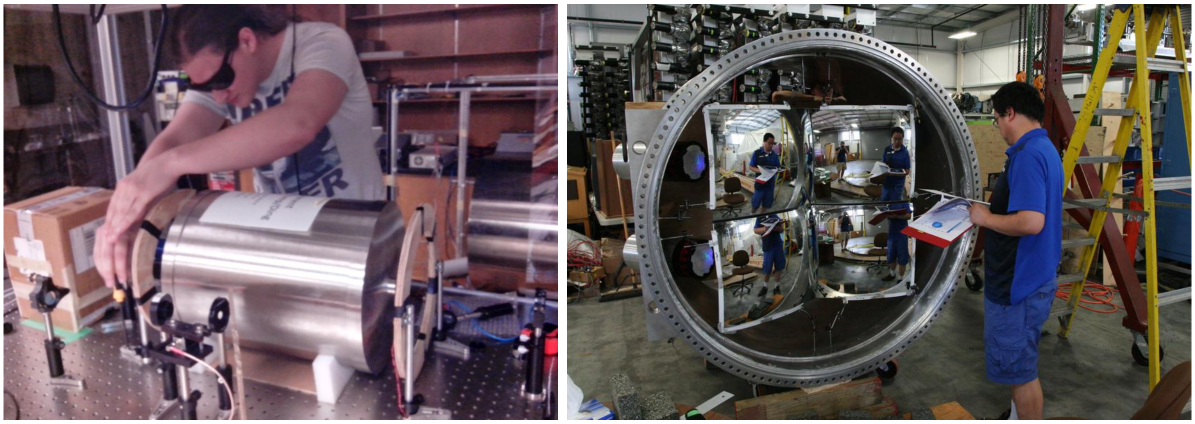


Figure 5.1: On the left a student is shown installing external magnet coils as part of neutron EDM R&D at the U. Winnipeg. On the right a U. Regina student is pictured checking mirror alignment of the SHMS Heavy Gas Cherenkov detector at JLab.

"I worked as a postdoctoral research associate at TRIUMF between April 2002 and December 2004. I received my Ph.D. in Experimental Nuclear Physics at the University of Liverpool in my native UK, and became a Canadian citizen during my time at TRIUMF. Since January 2005, I have worked as a Senior Research Scientist at Bubble Technology Industries (BTI) in Chalk River, Ontario. My work is primarily in applications of gamma-ray and neutron detectors in areas including homeland security, national defense, and dosimetry for the radiation protection of astronauts. This work is performed in collaboration with Government agencies such as the US Department of Homeland Security, the US Department of Defense, and the Canadian Space Agency. Many of the skills I learned at TRIUMF are directly relevant in my position at BTI. These skills include characterization of radiation detectors, analysis of complex multi-parameter data, computer programming, and design of data-acquisition electronics. Furthermore, my new role includes writing of scientific publications, public presentations, and funding applications, all areas that I was educated in during my time at TRIUMF."
Dr. Martin Smith (PDF, TRIUMF, 2002-2004), Senior Research Scientist, Bubble Technology Industries, Chalk River, ON

5.1 Overview of the skills acquired in nuclear physics training

Low and intermediate-energy nuclear physics experiments provide an ideal training ground for producing the technically savvy future generations of innovators. These smaller scale experiments give graduate students the opportunity to participate more fully in the overall experiment. They have a larger role in the collaboration, have the opportunity to gain experience with all aspects of the project, including the design, simulation, hardware development, measurement and data analysis. Due to the shorter time scale of nuclear physics experiments, students often get to participate in nearly every stage of the project, from conception to final results, and often take on leadership roles within the collaboration. In the process of building and running new facilities, designing and performing experiments and interpreting data, future scientists and engineers receive the training necessary to generate new ideas. This approach also cultivates valuable leadership skills. For example, a student on the Canadian Penning Trap experiment, Gang Li, who won the 2012 McGill Fessenden prize for the Design of a Centrifugal Cryogenic Pump (www.mcgill.ca/science/node/1957/#AWARDS), has a patent application underway. He is now a reactor physicist at Canadian Nuclear Laboratories in Chalk River, ON.

"UWinnipeg was the turning point in my road to success. The smaller class size at UWinnipeg reminded me of my education on the reservation and the faculty was encouraging. They would always gladly spend time outside of class to assist me with my coursework."
Mark Abotossaway (B.S. University of Winnipeg, 2010), Structural Analysis Engineer, Boeing, Seattle, Washington

> “During my third year in the undergraduate physics program at the University of Guelph, I spent the summer building the Gamma-Ray Escape-Supressed Spectrometer (TIGRESS) at TRIUMF in Vancouver. Situations I encountered at TRIUMF, like the extremely high precision required for much of the assembly, the tight timeline to have the project operational for the first experiment at the end of the summer, and the problem solving needed when issues arose during assembly- these experiences have stayed with me beyond the science and academic worlds. In fact, they have helped me immensely in my current role at Front Street Capital, where I work for a very prominent technology investor in Canada, Frank Mersch. In my role, I’m constantly trying to evaluate companies that are developing new technologies. I now have a better understanding of how long things take to build and modify, how serious problems that arise can be, and the quality of construction.”
> Brent Millar (B.Sc. Guelph 2008), Analyst, Front Street Capital, Toronto, ON

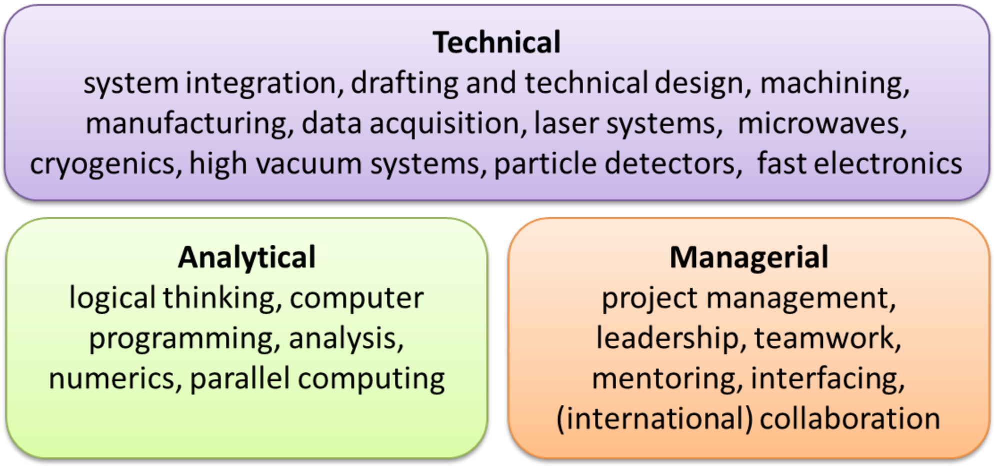


Figure 5.2: Skills gained during training in nuclear physics.

As another example, Mark Abotossaway is an Ojibwe from the Aundeck Omni Kaning First Nation. He graduated from the University of Winnipeg in 2010 and went on to obtain a dual degree in aerospace engineering from the University of Minnesota. During his time at the University of Winnipeg he received NSERC USRAs three years in a row, and also conducted research throughout the school year (supported by the Manitoba work-study program) on the Qweak focal-plane scanner and on the characterization of dead-layers in silicon detectors for neutron beta-decay using low-energy alpha and proton sources. As a student, he became a role model for aboriginal youth, volunteering at the University’s Aboriginal Student Services Centre. He is now a structural analysis engineer for Boeing, the world’s largest aerospace company, based in Seattle, Washington.

Highly qualified personnel trained in nuclear physics go on to be responsible for discoveries and technologies that will have an impact on our society in future, including significant roles in addressing societal demands on energy production and pollution reduction through development of new nuclear power plants, in addition to the above-mentioned medical applications.

> “For the past two and a half years I have been a Research Scientist with the Materials group at Ballard Power Systems located in Burnaby, BC. This leading-technology company develops and produces hydrogen fuel cells for a variety of applications such as back-up power in remote locations, fork-lifts, buses and automobiles. The Materials group is primarily focused on materials science of component parts of the fuel cells. My role is mainly to plan, perform, analyze and interpret data from measurements of material properties. The knowledge I gained while working on my M.Sc. with the Nuclear Physics group at the University of Guelph has benefited me in many ways in my current role. Writing my thesis has provided me with an excellent background in writing scientific reports, documenting experiments performed and summarizing results. During my work with the Nuclear Physics group I was also able to analyze large sets of data, developing my organizational and analysis skills. This has allowed me to excel in analyzing data at Ballard and my supervisors have highlighted this as one of my strengths. I believe it’s a great asset to the group.”
> Kathryn Green (M.Sc. Guelph, 2009), Research Scientist, Ballard Power Systems, Burnaby, BC

In the study of nuclear physics, students become proficient in a wide variety of skills in addition to acquiring knowledge related to various fields such as chemistry, electricity, high vacuum and computer systems. Examples of some types of skills include those listed in Figure 5.2. Many students go on to successful careers as professors or staff scientists at national and international facilities, while others leverage these skills in positions outside of academia in industries such as nuclear power, medical physics and even finance. As an example, Rob Pitcairn, who received an M.Sc. at the University of British Columbia working on the TRINAT project now works for a venture capital firm that invests in scientific projects.

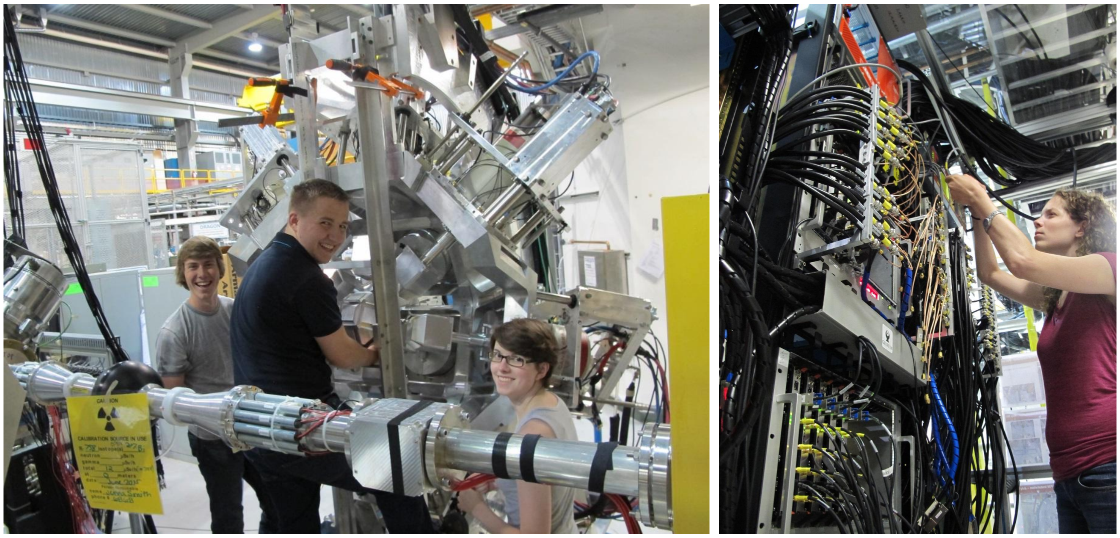


Figure 5.3: Students working with the gamma ray team at ISAC.

5.2 Canadians in nuclear physics

As a part of the SAP Long Range Plan Brief writing requested by NSERC, the Canadian Institute of Nuclear Physics (CINP) requested information from the nuclear physics community to gauge the dynamics and the demographics of the field in respect to the education and training of new personnel in the period of 2011-2016. PIs from 28 projects, representing faculty members from 17 universities and TRIUMF, submitted relevant information on HQP training as requested by CINP. Not all departments responded, and in some cases it was not clear that the responses were comprehensive. An active faculty is considered a faculty member that is engaged in an ongoing research program, either in a group or on their own, and can include emeritus professors. Undergraduate and graduate students considered are either funded by Canadian sources (NSERC or otherwise) or primarily supervised by Canadian investigators. There have been 10 new faculty hires in the last 5 years — 4 at TRIUMF, and 6 at Universities (Manitoba, Winnipeg, Guelph and McGill) — reflecting a growth and renewal of our community. In addition, as Figure 5.4 shows, there has been an increase in interest in nuclear physics at universities and TRIUMF.

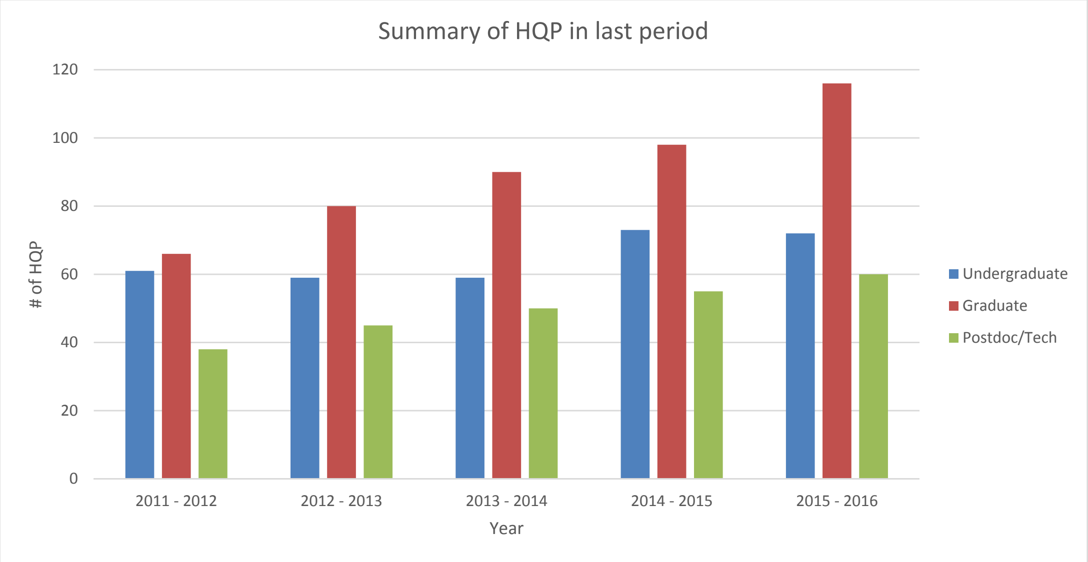


Figure 5.4: Plot of the number of highly qualified personnel receiving training in a given year for the period of 2011-2016. The numbers are for personnel either funded by Canadian sources (NSERC or otherwise) or primarily supervised by Canadian investigators.

Much of the growth in this period is due to the completion of several large facility upgrades and/or new experiments (ARIEL, EXO, γ-Ray Group, UCN), and is expected to continue (perhaps at a slower rate) as other large facility upgrades are completed and major new experiments ramp up (12 GeV JLab, MOLLER). Nearly all the groups had at least constant or modest growth in the number of HQP. In particular, the number of highly qualified personnel being trained at ARIEL has doubled over the past period, and those in TRIUMF theory have nearly tripled. The number of students and other HQP working on UCN has tripled to 30 people as well. There are also some relatively new projects such as EMMA, MOLLER, and muon g-2 that have begun training but have not yet reached their minimum level of personnel. Based on this trend and the scientific potential, it would be beneficial to continue the hiring of new faculty to replace members of our community that have recently retired and to capitalize on the new upgrades at TRIUMF and abroad. The observed trends are certainly encouraging and indicate a dynamic field, committed to training of highly qualified personnel through research.

5.3 Benefits to Canadians

> "I'm a prairie boy. I grew up in a small town. I had no idea what I was getting into when I decided to come to university. I am thankful I chose physics, because it led to this great opportunity to participate in international research."
> Brent Giesbrecht (B.Sc. Honours, University of Regina, 2012), Health Physicist, Cameco Corporation, Estevan, SK

Nuclear physics has produced a host of technologies that are now used as tools in many scientific disciplines, but also in more ordinary applications such as imaging technologies in medicine, cancer treatments, sterilization of blood and other medical items, oil-well logging, ion implantation of semiconductors, the most common type of smoke detectors, forensic analysis, monitoring cargo for contraband, and of course commercial power generation.

Accelerator production is a $2 billion industry, with 1000 accelerators sold yearly for applications ranging from semiconductor processing, producing short-lived isotopes for medical imaging, accelerator mass spectrometry, and for radiation therapy. The collective value of the products made using accelerator technology, including isotopes used in determining the age and origin of materials, studying the behavior of defects and impurities of materials, and medical applications has been estimated at more than $500 billion per annum [Physics Today 64, 46 (2011)]. Canada is one of six countries worldwide that can produce the superconducting radio-frequency (SRF) cavities needed in particle accelerators which have applications, not only for nuclear physics research at facilities like TRIUMF, but also in the energy, defence, aviation, aerospace and research industries to provide very precise metal-welding services using electron beams, and in environmental protection by replacing chemicals with electrons to treat flue gas that is emitted by coal-burning power plants.

> "My training in theoretical physics helped me, above all, to develop a superior way of thinking and of addressing a specific problem. Physics develops strong analytical skills, and physicists can - at the same time - be realistic and down-to-earth. Physicists not only phrase problems well, but can tackle them with pragmatism, and find optimal solutions. This way of thinking, of addressing and solving a possibly complex problem greatly helped me in my career in management consulting at a company that focuses on optimization. Our team has confronted very complicated business processes, and implemented solutions and systems that have saved our clients tens of millions of dollars. And our company currently employs about 30-40% PhDs in physics!"
> Octavian Teodorescu (PhD, McGill, 2002) Senior Consultant II, Princeton Consultants Inc. (www.princeton.com)

Figure 5.5: Saint Mary's U. students testing optical fibers for the JLab SBS Coordinate Detector.

> "My training in high-energy nuclear physics enabled me to develop skills and abilities that I now use in my everyday work. These include not only analytical skills in applied mathematics, but also, the ability to think critically, to formulate a well-formed research questions, and to discriminate between what is important and not when solving a problem. My hiring, as well as that of several of my colleagues, at the agency responsible for R&D at the Canadian Department of National Defence is a direct consequence of training in high-energy particle physics. I feel also confident that my employability throughout my career will be linked to my training in subatomic physics."
> Franois-Alex Bourque (PhD, McGill, 2008) Research Scientist, NATO Science and Technology Organization Centre for Maritime Research and Experimentation, Italy

Another example is Canada's long history of achievements in nuclear energy. CANDU reactors were developed in the 1950's and 60's and the design is still used today. Canadian nuclear researchers have take a leading role in a recently initiated International Atomic Energy Agency Coordinated Research Project for the "Development of a Reference Database for Beta-Delayed Neutron Emission" which has, among its research objectives, the goal to re-evaluate the beta-delayed neutron reactor constants in appropriate group format for energy applications and produce the recommended database.

These are just a few of the ways that fundamental nuclear physics research in Canada has had a substantial impact on society at large.

5.4 The next five years and beyond

In the coming years, several programs are coming on-line that will require a strategic increase in the investment in highly qualified personnel. In order to capitalize on the investment in the construction of new facilities, such as ARIEL and the JLab 12 GeV upgrade, it will be necessary to have the trained manpower to both run the equipment and staff the experiments. New experiments are anticipated to run in the next five years, requiring at least 10 graduate students and 4 postdoctoral researchers. This level of manpower is necessary to maintain the leadership role in these large international efforts. Postdoctoral researchers in theory are essential to these efforts as well, in order to calculate corrections and interpret the influx of new experimental results. These strategic investments in the training of a skilled and knowledgeable workforce will have benefits for many years to come.

> “Taking a physics degree is more than just learning physics equations and lab work. You gain a strong understand of computer science, math, and engineering. Most importantly you learn the importance of critical thinking and how to balance hands on work with mathematical calculations. One of the best experiences I had during my education was helping construct the GlueX barrel calorimeter. It is a great feeling knowing that something you have helped to make will be used in future research for years to come and that you are a part of such a huge research project that can have a profound impact to science.”
> Shaun Krueger (M.Sc., University of Regina, 2013), Software Support Specialist, iQmetrix, Regina, SK

5.5 Summary

Nuclear physics has and will continue to provide a broad range of benefits to society from the training of HQP to nuclear power, medical diagnostics and treatment. Technological advances made to further our understanding of the fundamental nature of matter have produced tools used by nearly every other scientific discipline. Innovations in detector and accelerator design will continue to impact medical, security and space applications.

> “Obtaining a degree in nuclear physics resulted in my learning a lot not only about physics, but also about computer science, mathematics, electrical/civil engineering, and countless other topics. The multidisciplinary approach to solving problems is exactly the kind of experience that led to my employment in Canada’s nuclear technology industry. I’m confident that very few, if any, academic programs could have prepared me as well for the work that I’ll be doing in my new position at Bubble Technology Industries Inc.”
> Dr. Scott MacEwan (PhD, University of Manitoba, 2015), Research Scientist, Bubble Technology Industries, Chalk River, ON

Chapter 6

Recommendations and Budgetary Estimates

In this chapter we present our detailed recommendations and budgetary estimates for prioritized endeavors.

Chapter 5 summarized clearly the growth in the nuclear physics community, and this brief in its entirety has demonstrated the breadth and dynamism of the research being conducted. Coupled together, there is little doubt that operating and capital funds must grow in coming years to ensure that Canadian researchers maintain a world-leading position in this field.

6.1 Major recommendations

Recommendation 1: Enhance nuclear theory support.

It is highly desirable to have a vibrant Canadian nuclear theory community which is intimately linked to Canadian experimental efforts in nuclear physics. The last five years have started to see the renewal of the Canadian nuclear theory effort, with several new hires who are recognized world leaders in their fields. Some evidence of this is in the high performance computing section 4.4, where advances in computing techniques and technologies have led to substantial progress in attacking a wide variety of complex theoretical nuclear physics problems. Some examples include large-scale *ab-initio* nuclear structure and nuclear reaction calculations, quantum Monte Carlo simulations of neutron stars and nuclei, relativistic quark-gluon plasma simulations, and multi-loop electroweak calculations.

A great opportunity exists to further strengthen and grow this program. The efforts of nuclear theorists in Canada are already well-aligned with the strengths of the Canadian experimental research in nuclear physics. A modest infusion of new funds will see substantial return in research productivity and results. We recommend strategic investment into nuclear theory HQP who can accelerate the efforts of these recognized world leaders at the fore-front of an exciting and fast-moving discipline.

Recommendation 2: Make strategic investments in additional HQP to capitalize on new or recently-upgraded facilities.

The last five years have seen the development of several major new experimental facilities, and large strategic investments in our field by domestic and international partners will lead to very significant increases in the available beamtime over the next five years. Full exploitation of the new scientific opportunities enabled by these facilities demands a corresponding increase in the NSERC subatomic physics envelope to support the research teams that will drive the scientific output from these major capital investments.

- At ISAC, DESCANT, GRIFFIN and IRIS have come online in the last 5 years, and TITAN has been extending its capabilities. In the next 5 years, as a result of the very substantive investments made by CFI, NRC, and its partners, the beamtime available to nuclear physics experiments will increase dramatically. This will allow a large number of high priority measurements to more quickly move ahead. Starting in 2018, an extra 5 weeks of beam per year is expected as ARIEL begins beam delivery to the β-NMR facility. A more dramatic increase will come in about 2020, as the available beam time doubles to roughly 320 days per year as photo-fission on actinide targets begins at ARIEL. The high impact measurements enabled by these investments require a further ramp-up of HQP starting about 2018 in order to maximize the potential scientific output.
- At Jefferson Lab, detectors have been constructed by Canadians for Halls D,C,A as part of the 12 GeV upgrade, and experimental work is now ramping up. The GlueX experiment formally starts in 2016, and the kaon, pion and proton form factor experiments ramp up from 2016-18. The MOLLER experiment anticipates first beam in 2020. These Canadian-led experiments are actively recruiting new students and PDFs now.
- With the start of the ELENA facility and the largely Canadian-funded ALPHA-g project, ALPHA-Canada will be doubling its productivity by simultaneously operating ALPHA-2 for precision spectroscopy and ALPHA-g for gravity measurements. These Canadian-led high-profile initiatives require an increased HQP support in order to fully capitalize the large investments made by Canada.
- Activities relating to the TRIUMF UCN source have also been quickly increasing. Commissioning of the source is planned for 2017, with Phase 2 upgrades planned for the coming decade to enable world-leading capabilities.

The experimental studies enabled by these new facilities have very high scientific merit, as otherwise the cases for building them could not have been successfully made. Full scientific exploitation of these opportunities will require corresponding increases in investment, particularly for HQP. Unless new investments of this nature are made, the Canadian nuclear physics community could ultimately find itself unable to capitalize on the new scientific opportunities provided by the major capital investments which have been made in world-class experimental equipment.

Recommendation 3: Maintain a diverse program of excellence in experimental and theoretical nuclear physics research.

Nuclear physics addresses many of the most important scientific questions which exist today. We have listed in Chapter 1 what are considered internationally the most important open questions in nuclear physics research. By making best use of its established expertise and strengths, and seeking to contribute to the fields of greatest scientific opportunity, the Canadian nuclear physics research community has self-selected where to best concentrate its efforts. In Chapter 3, we have shown how the Canadian research effort contributes to our better understanding of the solution to these major questions, and the field is dynamic, with the community moving its manpower and resources to the inquiries of highest scientific priority.

Despite this natural evolution and concentration of efforts, we caution that it is important to not make the Canadian research contributions too narrow. Nuclear physics is a many-body problem, and history has shown that it is not possible to predict where the next breakthrough will come from. Surprises have come from what might otherwise have been considered to be straightforward measurements, and advances towards the solution of one major question often depends on progress in a complementary area. For example, many searches for physics beyond the Standard Model depend on detailed knowledge of nuclear matrix elements, and hence the field of fundamental symmetries depends greatly on knowledge of nuclear structure. In the astrophysical regime, the determination of neutron star properties relies greatly on knowledge of the QCD equation of state. There are also deep connections between the fields of nuclear structure and nuclear astrophysics, particularly for a better understanding of the r-process abundance distribution.

We strongly recommend that a diverse program of experimental and theoretical research excellence addressing all of the key questions of nuclear physics be maintained in all funding scenarios.

Recommendation 4: Provide capital funding for future high impact experiments.

The Canadian nuclear physics community has focused its activities to address the major scientific questions as enumerated in Chapter 1, and it has been very successful in not only obtaining substantial funds from CFI and NSERC, but also in taking advantage of major investments by international partners abroad. While it is poised to reap the scientific benefits of these investments, it faces the need to prepare for the next generation of projects in order to maintain Canadian research excellence in the future.

Several major experimental initiatives under development promise notable improvements over current knowledge, and will require significant capital funding if these gains are to be realized.

- The largest projects that are the most advanced in terms of positive international review and technical preparation are the UCN facility at TRIUMF and the MOLLER experiment at JLab. Both are expected to seek CFI funds. The SoLID experiment at JLab is expected to follow 1-2 years later.

- The decision by the USA to consider siting a tonne-scale neutrino-less double-beta decay experiment at SNOLab is a very positive development. If nEXO is selected in the DOE decision-making process, it will allow Canadians to leverage considerable international resources in a world-class experiment.

- Several longer-term upgrades of ISAC experimental equipment are in the early planning stages, including $LaBr_3$ detectors for DRAGON/EMMA, a silicon tracker array for TIGRESS, and EMMA-trap. These have not yet been vetted by external reviews, so further refinements of the planned upgrades are likely, and only approximate budgetary estimates can be provided at this stage.

- Other opportunities may also arise at future international endeavors, such as the presently constructed in-flight facilities at FRIB or FAIR.

In summary, the future progress of experimental knowledge depends on continuing investments in new experimental techniques and apparatus. In many cases, these investments have the further benefit of enabling technology-transfer to Canadian industry.

Recommendation 5: Provide funds for next-generation detector and accelerator R&D.

Canada has benefited from past R&D investments. For example, Canadians have been able to make leading contributions in large international experiments (e.g. Qweak and GlueX at JLab) as a result of detector R&D done in Canada, and the ARIEL eLINAC project has enabled PAVAC Industries Inc. (Richmond, BC) to expand and become one of a handful in the world able to construct SRF cavities.

Over the much longer-term, there are several exciting opportunities for Canadian nuclear physicists in the next-generation of experiments that will require ongoing investments in detector and accelerator R&D.

- As discussed in Secs. 3.1.3.3 and 4.2.4, there is considerable international interest in the construction of an Electron-Ion Collider in the coming decade. Both Brookhaven and Jefferson Laboratories have advanced proposals that have been reviewed by NSAC. It is expected that the further development of these proposals will form one of the major recommendations of the next USA Nuclear Physics Long Range Plan, with site selection to take place within the next few years. Canadian nuclear physicists are starting to become active in the planning and prototyping for this new facility.

- As discussed in Secs. 3.2.3, 4.1.1.4 and 4.3.2, longer-term possibilities for the future development of ARIEL are starting to be considered. One possible upgrade option for ARIEL/ISAC includes the extension of the energy range of the ISAC-II SRF linac, and feeding the beams into a new heavy-ion storage ring for in-ring experiments or secondary fragmentation to access very neutron-rich isotopes. Such proposals are in very early discussion stages and have not yet undergone external review and costing.

In both cases, the technical challenges to realize these designs are substantial. R&D investments are vital to assure the continued excellence of Canadian nuclear physics research in coming decades.

6.2 Budget estimates to implement recommendations

As a part of the SAP Long Range Plan Brief writing requested by NSERC, the CINP requested budgetary information from the nuclear physics community under two scenarios:

- the amount that would give the optimum scientific return for the support investment (i.e. the best benefit to cost ratio, bearing in mind the scarcity of funds).

- the minimum amount which would still permit a viable (but perhaps sub-optimal) program.

	More extensive (optimal)		Restrained (minimum viable)		Operating Difference (%)
	Capital (Total $k)	Operating ($k/yr)	Capital (Total $k)	Operating ($k/yr)	
Nuclear Theory	570	675	420	450	49
ALPHA-2/g	975	1400	750	800	75
ISAC Experiments					
Gamma Ray Team		2710		2220	22
TITAN		800		590	36
All other ISAC	525	1510	320	905	67
ISAC Upgrades					
DRAGON/EMMA	1350		200		
EMMA-trap	1200		1200		
All other ISAC	800		800		
Jefferson Lab					
MOLLER	2500	370	250	270	37
SoLID	1500	350	250	250	40
All other JLab		690		490	41
nEXO	1560	1200	1200	530	126
UCN	12000	800	12000	600	33
All other initiatives	450	705	450	545	29
SUM	23435	11205	17835	7650	46

Table 6.1: Projected operating cost per year, and total capital requirements to completion of project. Projects with an operating cost >$500k/year or a capital cost >$1M are indicated separately. Please note that we have not independently vetted any of these numbers, they are given to us as a result of community consultations. With the exception of nuclear theory, items are listed alphabetically. The sum may not add exactly to the total of the individual items due to rounding.

These funds would include resources needed from NSERC, CFI and other agencies.

The community response was very good. Principal Investigators from 28 projects, representing faculty members from 17 universities and TRIUMF provided budgetary information which was used to arrive at the estimates presented in Table 6.1.

6.2.1 The optimal scenario

Based on the input received from the community, substantial operating investments are needed to fully capitalize on the available scientific opportunities. The proportionally larger increases projected by ALPHA-Canada and nEXO-Canada are driven by recent and projected expansions of their collaboration and recent or projected major capital investments. The other experimental operations request increases of about 35% over the next 5 years, primarily for an increase in students and postdocs needed for full scientific exploitation of the newly operational equipment and substantive increases in available beamtime expected over the next planning period. Thus, we estimate the cost of recommendation 2 for these projects to be approximately $2.05 million over five years, corresponding to an increase of just 6.2% per annum. This infusion of funds will ensure continuing Canadian leadership in these fields.

Table 6.1 also shows the requested increases in nuclear theory support, based on the input received. It is seen there that the nuclear theory budget is underweight relative to the size of the total nuclear community, well under the 10% threshold typically expected to maintain a vibrant effort in theoretical physics. Clearly, a modest infusion of new funds would pay significant dividends, and this investment is clearly justified by the world-class talent that Canada has recently recruited from abroad. Recommendation 1 corresponds to an approximate 50% increase in support for the current Canadian nuclear theory researchers and represents a modest increase in funding of only about $250k over five years. If Canada is able to recruit additional top talent, then this number would increase accordingly.

6.2.2 Restrained (minimum viable) scenario

The minimum viable program is estimated at $7.65 million operating per year and does not address recommendations 1 and 2. In many cases, this corresponds to what the research groups receive now. In this restrained funding scenario, the Canadian nuclear physics community could ultimately find itself unable to capitalize on the new scientific opportunities provided by the ARIEL and JLab 12 GeV facilities and the major capital investments which have been made in world-class experimental equipment both domestically and abroad. Full exploitation of these new scientific opportunities requires a corresponding increase in the NSERC subatomic physics envelope to support the research teams that drive the scientific output from these major capital investments.

6.2.3 Major capital investments

The two large future capital investments which are the most advanced technically are the UCN facility at TRIUMF and the MOLLER experiment at JLab.

The UCN facility has already received $4.2 million from CFI and TRIUMF in-kind support, for a total project cost of $11.1 million when including contributions. This part of the project (phase 1) is expected to be completed by early 2017. The amount listed here is for an envisioned major upgrade to both the UCN source and neutron EDM experiment (phase 2). A total $12 million future request (including partner contributions to leverage CFI resources) is anticipated. This would enable an upgrade of the cold neutron moderator, giving rise to a factor of five increase in UCN production. Further improvements to the superfluid helium cryostat may also be made, depending on experience gained from the first two years of operation at TRIUMF. The main part of the phase 2 request would be a new neutron EDM apparatus, capable of achieving 10^{-27} e·cm precision, which is approximately an order of magnitude better than the best achieved so far.

MOLLER is projected to be a US$25 million experiment, not counting operating costs. The projected Canadian contribution is roughly 10% of the total. For reference, the Canadian funding to the recently completed Qweak experiment at JLab was closer to 20%, due to contributions to electronics, detectors and the magnetic spectrometer. As a result of successful and substantial contributions by the Canadian group to Qweak, they have become internationally well-known in the area of fundamental symmetries experimentation, and have assumed prominent roles in the planning of the new experiment. In the optimal scenario, they request to be funded to contribute to hardware development and production at the level of $2 million over the course of the major construction period from 2017 to 2020. Under the more limited scenario, the hardware contributions would be reduced to ADC board electronics for the integrating detectors only. The MOLLER Collaboration is now preparing for the Critical Decision (CD) process to acquire DOE funding for the project, with data taking currently projected for 2021-23.

As already mentioned, possible future upgrades of ISAC detector systems are in the early planning stages. Very early estimates place these requests between $2 and 3.5 million, depending on the nature and extent of the upgrades.

6.3 Non-budgetary recommendations

The importance of the Team Discovery Grant Program in subatomic physics

The Subatomic Physics Team Discovery Grant Program has a number of very attractive features for Canadian nuclear physicists. A key example is the Gamma-Ray Spectroscopy Team grant. The 5-year grant permits a long-term view to program, personnel and infrastructure planning and maximizes the efficiency with which operating resources are used to support the overall program. Simultaneously, the responsiveness inherent in the Team Grant program permits the group to stay at the forefront of a field in which experiments are performed, new results emerge, new beam developments occur, and new research opportunities arise on timescales much shorter than the operating grant cycle. While the Team Grant mechanism remains within subatomic physics, in light of the recent cancellation of the Team Grant program outside of the subatomic physics envelope, it is important to stress this unique combination of factors, particularly in low-energy nuclear physics research, that continue to make the Team Grant funding mechanism a vital component in the management of the NSERC subatomic physics envelope.

Suggested improvements to NSERC's CREATE program

The NSERC CREATE program is designed to enhance the workforce readiness of HQP, and it is having a positive impact on our community through e.g. the IsoSIM CREATE program at UBC and TRIUMF. However, the structure of the CREATE program limits its impact. The CINP has looked very closely to see if the CREATE program can be used to support a national HQP training program in fundamental nuclear physics research. This would not only provide enhanced opportunities for the next generation of physicists, but it would also allow access to an additional source of training funds outside the SAP envelope. Although the CINP decided to keep this possibility in mind for the future, it will not be pursued in the next few years. There were several reasons for this, including the difficulty to receive the required large financial contribution from the lead university and their strong support for what in the end would be a national program, and the requirement that the lead university must have a compelling tie to companies of direct relevance to nuclear physics research. Neither of these requirements seemed a natural fit to our community. It would be helpful if the CREATE grant requirements could be made more flexible, to allow national HQP training programs to more easily fit within the program guidelines (e.g. if the role of the lead institution could be de-emphasized, the project investment could more easily be spread over several institutions). Alternatively, additional funds could be added to the SAP envelope to support HQP training.

Appendix A

List of Acronyms

ALPHA (Antihydrogen Laser PHysics Apparatus): An experiment at the CERN Antiproton Decelerator trapping and studying the properties of antihydrogen atoms.
ANL (Argonne National Laboratory): A DOE national laboratory in Argonne, Illinois, which is home to a number of facilities, including the ATLAS heavy-ion accelerator.
ARIEL (Advanced Rare IsotopE Laboratory): A project to enhance TRIUMFs capabilities to produce rare isotope beams and to showcase new Canadian accelerator technology.
ATRAP (Antimatter TRAP): An experiment at CERN trapping and studying the properties of antihydrogen atoms.
BNL (Brookhaven National Laboratory): A DOE national laboratory in Upton, New York, which is home to a number of facilities including RHIC.
BRIKEN (Beta-delayed neutron studies at RIKEN) Large ^{3}He-long counter neutron detection array with an implantation detector which will take data at RIBF from 2016 on.
CANREB (CANadian Rare-isotope facility with Electron-Beam ion source): A CFI-funded initiative that will improve the purity of rare ion beams delivered by ARIEL to ISAC.
CARIBU (CAlifornium Rare Isotope Breeder Upgrade): A facility for creating neutron-rich rare isotopes at Argonne National Laboratory.
CERN (Centre European pour la Recherche Nucleaire): The European Organization for Nuclear Research, based in Geneva, Switzerland.
CFI (Canada Foundation for Innovation): Created by the Government of Canada in 1997, CFI makes investments in state-of-the-art research facilities and equipment in a wide variety of scientific disciplines.
CINP (Canadian Institute of Nuclear Physics): The organization that gathered input from the Canadian nuclear physics research community in order to put together this document.
CPT (Canadian Penning Trap): The CPT spectrometer is designed to provide high-precision mass measurements of short-lived isotopes. It is located at the Argonne National Laboratory in Argonne, Illinois.
DESCANT (DEuterated SCintillator Array for Neutron Tagging): A neutron detector array to be used at ISAC.
DOE (Department of Energy): The United States Department of Energy, which operates a number of national laboratories across the USA.
DRAGON (Detector of Recoils And Gammas Of Nuclear reactions): A detector designed to measure the rates of nuclear reactions important in astrophysics, based at ISAC-I.

EDM (Electric Dipole Moment): Permanent electric dipole moments are forbidden for fundamental particles by time reversal violation.

EIC (Electron-Ion Collider): A new DOE nuclear physics user facility proposed to be housed at either Brookhaven National Lab or Jefferson Lab.

ELENA (Extra Low ENergy Antiproton ring): Antiproton cooling and deceleration ring, under construction as an upgrade to the Antiproton Decelerator at CERN.

EMMA (ElectroMagnetic Mass Analyzer): A device being constructed to study the products of nuclear reactions involving rare isotopes at ISAC-II.

EXO (Enriched Xenon Observatory): An experiment seeking to measure neutrinoless double beta-decay in ^{136}Xe. The experiment is currently located at the WIPP facility in New Mexico, USA. A substantially larger next-generation detector nEXO is proposed for SNOLab.

FAIR (Facility for Antiproton and Ion Research): An accelerator facility for studying nuclear structure and nuclear matter, presently under construction as upgrade of the GSI facility in Darmstadt/ Germany.

FRIB (Facility for Rare Isotope Beams): A new DOE user facility for nuclear science, under construction on the campus of Michigan State University.

FrPNC (Francium Parity Non-Conservation): An experiment to study atomic parity non-conservation in francium, based at ISAC-I.

GlueX (Gluonic Excitations Experiment): An experiment seeking to identify hybrid mesons with explicit gluonic degrees of freedom at Jefferson Lab Hall D.

GPD (Generalized Parton Distribution): A recently developed approach to better understand hadron structure by representing the parton distributions as functions of more variables, such as the transverse momentum and spin of the parton.

GRIFFIN (Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei): A detector at ISAC-I for studying nuclear decays at high resolution.

GSI: Formerly "Gesellschaft fuer Schwerionenforschung", now GSI Helmholtz Center for Heavy Ion Research in Darmstadt, Germany.

HERA: A former electron proton collider at the DESY laboratory in Hamburg, Germany.

HPC: High-Performance Computing

HQP (Highly Qualified Personnel): Personnel obtaining advanced skills as a result of NSERC-funded research, including students, postdocs and technicians.

IAEA (International Atomic Energy Agency): Set up within the United Nations family in 1957 as the world's centre for cooperation in the nuclear field, the Agency works with its Member States and multiple partners worldwide to promote the safe, secure and peaceful use of nuclear technologies.

ISAC (Isotope Separator and ACcelerator): A rare isotope accelerator facility, based at TRIUMF. There are two experimental halls, ISAC-I and ISAC-II.

ISOL (Isotope Separation On-Line): A technique of radioactive ion production in which proton spallation of a thick target is used to produce a wide range of radioactive fission fragments.

ISOLDE (Isotope Separator On-Line DEtector): An On-Line Isotope Mass Separator facility at CERN for the study of low-energy beams of radioactive isotopes .

JLab (Jefferson Lab): The Thomas Jefferson National Accelerator Facility, located in Newport News, Virginia.

J-PARC (Japan Proton Accelerator Research Complex): A high intensity proton accelerator facility located in Kamioka, Japan.

MAMI (Mainz Microtron): An electron accelerator facility, located on the campus of the Johannes Gutenberg University of Mainz, Germany.
Majorana: An experiment whose objective is to study double beta-decay in ^{76}Ge.
MOLLER: An experiment to measure the parity-violating asymmetry in electron-electron (Moller) scattering at Jefferson Lab.
NLO/NNLO (Next to Leading Order/Next-to-Next to Leading Order): increasing level of complexity of various types of loop diagrams.
NSAC (Nuclear Science Advisory Committee): An advisory committee that provides official advice on basic nuclear science research to the U.S. Department of Energy (DOE) and the U.S. National Science Foundation (NSF).
NSERC (Natural Sciences and Engineering Research Council of Canada): An agency of the Government of Canada that supports university students in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian companies to participate and invest in postsecondary research projects.
NuPECC (Nuclear Physics European Collaboration Committee): Co-ordinates nuclear physics research planning as an Expert Committee of the European Science Foundation.
pQCD (Perturbative QCD): QCD in the hard-scattering regime, where perturbative methods can be reliably employed, as opposed to the non-perturbative regime where they cannot.
PREX/CREX (Lead (Pb) Radius Experiment/ Calcium Radius Experiment): Two experiments at Jefferson Lab utilizing parity violating electron scattering to determine the neutron radius of these nuclei, as opposed to their charge or matter radii.
PVES: Parity Violating Electron Scattering.
QCD (Quantum ChromoDynamics): The theory describing the fundamental interactions between quarks and gluons.
RCNP (Research Centre for Nuclear Physics): A national centre for nuclear physics, based in Osaka, Japan.
RHIC (Relativistic Heavy-Ion Collider): A high-energy heavy-ion collider facility based at Brookhaven National Laboratory.
RIB: Rare/ radioactive ion beam.
RIBF (Rare Isotope Beam Factory): A user facility for nuclear science, located at RIKEN.
RIKEN (The Institute of Physical and Chemical Research): Japan's largest comprehensive research institution that performs research in a diverse range of scientific disciplines, including physics, chemistry, medical science, biology and engineering. Founded in 1917 as a private research foundation in Tokyo, RIKEN has grown in size and scope, and now encompasses a network of research centers and institutes across Japan.
SAL (Saskatchewan Accelerator Laboratory: The former electron accelerator at the University of Saskatchewan.
SAP (SubAtomic Physics): The broader field of nuclear and particle physics, comprising all knowledge taking place at scales smaller than that of the atom.
SBS (Super Big-Bite Spectrometer): A moderate acceptance magnetic spectrometer under construction for Jefferson Lab Hall A.
SoLID (Solenoidal Large Intensity Device): A high luminosity, large acceptance detector proposed for Jefferson Lab Hall A that makes use of the former CLEO solenoid magnet.
SHMS (Super High Momentum Spectrometer): An 11 GeV/c superconducting magnetic spectrometer nearing completion at Jefferson Lab Hall C.
SM (Standard Model): The standard model of elementary particle interactions.

SNO+: An experiment under construction at SNOLab, whose objective is to use the infrastructure from SNO to study double beta-decay and lower- energy solar neutrinos using a liquid scintillator instead of heavy water.

SNOLab: An underground science laboratory specializing in neutrino and dark matter physics, based in Sudbury, Canada.

SPIRAL II: A heavy-ion accelerator facility in Caen, France.

SRF (Superconducting Radio Frequency): Acceleration of charged particles via the use of superconducting cavities operating in the radio frequency range. Several examples include the ISAC-II and ARIEL accelerators at TRIUMF, and the Continuous Electron Beam Accelerator at Jefferson Lab.

TASCC (Tandem Accelerator SuperConducting Cyclotron): The former heavy-ion accelerator at Chalk River.

TIGRESS (TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer): A detector at ISAC-II for studying nuclear decays at high resolution.

TITAN (TRIUMFs Ion Trap for Atomic and Nuclear science): An ion trap facility at ISAC for high-precision mass measurements of rare isotopes.

TRINAT (TRIUMF Neutral Atom Trap): A device to trap and study the radioactive decays of neutral atoms, based at ISAC-I.

TRIUMF: Canada's national laboratory for particle and nuclear physics, based in Vancouver, BC.

TUDA (TRIUMF U.K. Detector Array): A detector designed to measure the rates of nuclear reactions important in astrophysics, based at ISAC-I.

UCN (Ultra-Cold Neutron): A CFI-funded facility to study neutron properties at high precision, soon to be sited at TRIUMF.