Nuclear Physics Brief to the Subatomic Physics Long Range Planning Committee

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1. Introduction

The nuclear physics community has gathered together to outline its vision for the next 5-10 years. That vision is summarized in this brief, prepared by a representative committee struck at the DNP business meeting at Vancouver in June, 2005 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 Long Range Planning Committee as it works to establish the vision and goals for the whole subatomic physics community in Canada.

Nuclear physics is driven by fundamental investigations on the origin, evolution and structure of strongly interacting matter. This is a far-reaching mission that requires a balanced program of experimental and theoretical effort 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 exactly what these questions are, as they are given in nearly identical forms by both the U.S. Nuclear Science Advisory Committee (NSAC) report in 2002, and the Nuclear Physics European Collaboration Committee (NuPECC) report in 2004. Here, we give a summary of these five questions and use them to place the Canadian nuclear physics effort in an international context.

Question 1: Can we understand hadron structure and interactions in terms of 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 and Europe, with goals of obtaining: a tomographic view of the quarks and their motion within the nucleon; a detailed understanding of the how QCD gives rise to the properties of the lighter hadrons, and; how these properties are modified when they are placed in a nuclear environment. Canadians have leadership roles in a number of experiments at offshore facilities, including studies of the nucleon resonance mass spectrum, and detailed measurements of proton and pion structure. 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.

The G^0-forward angle results from Jefferson Lab are an example of a Canadian achievement in this area. The purpose of this experiment is to quantify the contribution of the strange-quark sea to proton structure. Measurements of parity-violating asymmetries in elastic electron-proton scattering are used to determine the strange quark form factors of the proton. The experiment requires two measurements, at forward and backward electron scattering angle, to separately determine the strange electric and magnetic form factors. To date, the forward-angle portion of the experiment has been published by the G^0 Collaboration (D.S. Armstrong *et al.,* Phys. Rev. Lett. **95,** 092001 (2005)) which has significant participation from Canadian physicists. These results, for a linear combination of the two form factors, cover a much larger range of Q^2 than previous measurements, and confirm that the strange-quark contribution to proton structure is small but nonzero. The results are compared to a recent Canadian-led Lattice QCD calculation of the two form factors. The forward-angle results and the lattice calculation are consistent within systematic uncertainties, but a more stringent test of these predictions will be provided after the backward-angle part of the experiment is completed.

Question 2: What is the structure of nuclear matter?

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 for the next 5-10 years. Worldwide, this has driven the recent development of high-quality and multi-faceted 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. At present, and for the coming decade, the ISAC facility at TRIUMF is the world leader in the emerging technology of radioactive beams, and Canadians have a unique opportunity to make substantive advances in the field. 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.

The Canadian nuclear structure community has spent much of the past 5 years building and commissioning infrastructure needed to support a full program of research at TRIUMF-ISAC. The 8π spectrometer has been installed and furbished with auxiliary detectors to become a world-unique device; the TIGRESS spectrometer, representing a major step forward in γ-ray detector technology, has been developed and is currently being installed; and the TITAN facility, again representing a leap forward, was developed and is being built. An early highlight from the physics program just underway with the 8π spectrometer was the measurement involving the β-decay of the neutron-halo nucleus ^{11}Li. The neutron halo in ^{11}Li has such an extended spatial distribution that ^{11}Li has a similar "size" to ^{208}Pb. A surprising result (Sarazin *et al*., Phys. Rev. C **70**, 031302(R) (2004)) was evidence that the neutron halo, rather than being "fragile", could not only survive the process of β-decay from ^{11}Li to ^{11}Be, but also the ^{11}Be neutron emission to ^{10}Be as shown in Figure 1-1. This result will lead to an increased understanding of one of the key phenomena in the nuclear many-body system, that of pairing, which plays a major role in the structure of nuclei.

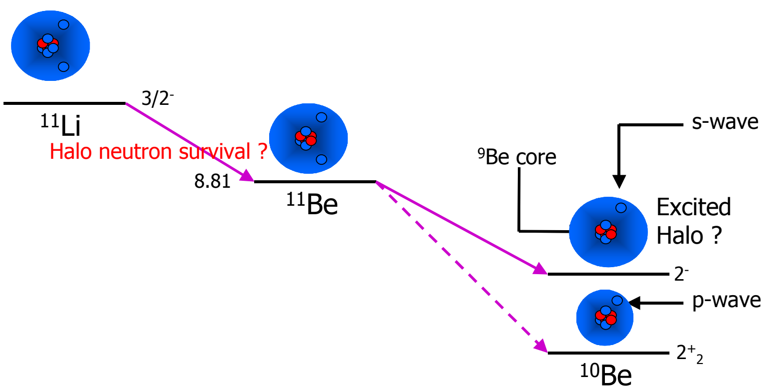

Figure 1-1: *β-decay of ^{11}Li leads to excited states in ^{11}Be that decay by neutron emission. By analyzing the states that are populated in ^{10}Be, and comparing with calculations of their structure, evidence for the survival of the neutron halo was found. This may represent one of the simplest systems in which to study nuclear "Cooper" pairs.*

Question 3: What is the role of nuclei in shaping the evolution of the universe?

Primordial nucleosynthesis, nucleosynthesis that occurred during the cooling immediately following the Big Bang, gave rise to primordial abundances of H, He, and Li. All other chemical elements in the universe were produced as a result of nuclear reactions occurring in stars, during supernova explosions, novae, 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 mechanism of core-collapse supernovae; the structure and cooling of neutron stars; the origin, propagation, and interactions of the highest-energy cosmic rays; and the nature of galactic and extragalactic gamma-ray sources. 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 nuclear reactions involving short-lived nuclides of relevance to astrophysics. These include measurements of the various nuclear capture processes and the determination of masses, half-lives, and structures of rare nuclei that occur in cataclysmic stellar environments, such as novae or supernova explosions. Canadians working at the ISAC facility at TRIUMF play a key role in this active field with the unique DRAGON spectrometer, complementing experiments underway at GANIL in France and ISOLDE at CERN. The new detectors being built or proposed for ISAC and ISAC-II will also play key roles in this program and ensure that TRIUMF stays at the forefront of this area of research.

A major accomplishment of the Canadian community has been the determination of the ^{21}Na(p,γ)^{22}Mg reaction rate. This particular reaction is one of the most important reactions determining the abundance of galactic ^{22}Na produced in explosive scenarios, as in novae or X-ray bursters. Previously, it was believed that the ^{22}Na production would be sufficient to allow it to be detected by γ-ray astronomy via its primary decay γ-ray of 1275 keV. A major dilemma was the fact that both the COMPTON and INTEGRAL satellites did not observe this decay. Direct measurements of this reaction, performed using a radioactive beam of ^{21}Na with the DRAGON facility at TRIUMF-ISAC (Bishop *et al*., Phys. Rev. Lett. **90**, 162501 (2003)), however, measured the ^{21}Na(p,γ)^{22}Mg reaction rate to be higher than previously estimated, resulting in ^{22}Na production much earlier in the nova. This earlier production allows for an increase in the amount of ^{22}Na that is destroyed by the ^{22}Na(p,γ) reaction. The net result is that the amount of ^{22}Na produced is much lower than previously estimated, consistent with the observations of the γ-ray satellites.

Question 4: 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, such as super-symmetry, which offers a possible explanation for the dark matter of the universe. 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.

i. The universe has an obvious imbalance of matter and antimatter, but 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 ISAC, Canadian researchers test time-reversal symmetry by searching for permanent electric dipole moments in atomic systems. These studies are complemented by permanent electric dipole moment searches using cold neutrons at LANSCE and SNS in the USA, and attempts to measure time-reversal violation in the charged kaon sector at KEK and J-PARC in Japan. Finally, the Antihydrogen Symmetry Test at CERN will test our understanding of antimatter by directly comparing the atomic spectra, and possibly gravitational acceleration, of hydrogen and antihydrogen.

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ii. Another key question is the nature of the ”superweak” 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 will 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.

iii. Finally, the resolution of the solar and atmospheric neutrino puzzles by SNO and Super-Kamiokande opens up possibilities for exciting discoveries in the neutrino sector. A key question is the nature of the identified neutrino oscillation. 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.

Major recent achievements by Canadian groups have been reported in 2005 in the three publications of the first results from the TWIST experiment for muon decay (Phys. Rev. Lett. **94** 101805(2005)) and Phys. Rev. D **71** 071101(R)(2005)) and from the TRINAT group on the b-ν correlation parameter (Phys. Rev. Lett. **94** 142501 (2005)). The TWIST measurements gave a new constraint on right-handed muon interactions and on left-right symmetric models while the TRINAT result places the best limit on scalar interaction in semileptonic decays for the quarks of the first generation.

Question 5: What are the phases of nuclear matter?

Nuclei are an important manifestation of nuclear matter, since they 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. Nuclear matter can also be heated by absorbing energy from a relativistic collision. In this case, `nuclear temperatures' can reach values that represent the 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, GSI in Germany and the LHC at CERN. Canadian experimental researchers have been selective in the nuclear physics they pursue, and they have decided to concentrate their efforts on the other four of these five key physics questions, where their contributions have greater impact. However, 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 for terrestrial searches for the quark-gluon plasma, and for our understanding of astrophysical phenomena such as neutron star structure and the evolution of the early universe.

In the sections following the Executive Summary, we will discuss the contributions of Canadians to four of these five questions in greater detail, showcasing a number of recent accomplishments, 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 coming decade.

2. Executive Summary of Recommendations

In this report, we make many detailed recommendations. They can be summarized in terms of five key recommendations.

1. Maintenance of a broad-based program in Canadian nuclear physics.

The Canadian nuclear physics program is grouped around several key physics questions that are internationally recognized as each being of high priority. Canadians lead or make key contributions addressing each of these questions in a variety of experimental and theoretical initiatives both in Canada and abroad. With significant advances occurring in multiple domains, it is clear that a broad-based nuclear physics program addressing these key questions must be maintained in all funding scenarios.

2. Completion and exploitation of the new facilities at ISAC and ISAC-II

A large investment has been made by Canada in the new ISAC and ISAC-II infrastructure at TRIUMF. The completion of the experimental facilities and the associated operational funds necessary to make best use of this infrastructure should be a high priority for funding from the GSC-19 envelope, as this will allow the maximum physics impact to be made from these investments.

3 .Further development of the TRIUMF experimental capabilities.

ISAC currently boasts the highest primary driver beam power among the world's ISOL-based radioactive beam facilities. For this facility to realize its full potential, however, an intense program of ion-source and target development over the next several years is required. Many high priority aspects of the nuclear physics program described in this document depend on these advancements, and thus the continued development of these capabilities is required.

To satisfy the increasing demands for beam time from the ISAC scientific community, it is crucial that the proton economics at TRIUMF be improved by upgrading the cyclotron intensity and providing a second ISAC production line. Considering some of the long term prospects mentioned for the fundamental symmetry test program (UCN, Muons) , it is important that the only accelerator group in Canada keeps abreast of high power proton accelerator research and development worldwide.

4. Opportunities for significant Canadian impact in offshore nuclear physics research should be fully exploited.

Hadron physics studies, fundamental symmetry tests, and moderate-energy tests of the Standard Model form a major part of the international nuclear physics effort. Building upon a long history of research in these areas, Canadians have distinguished themselves by making a number of high impact contributions to both theory and experiment. Historically, the impact to investment ratio of this research has been very favourable to Canadian science, and the nuclear physics program outlined in this document describes these opportunities in greater detail. The culmination of this effort will require significant funding as well as the continuation and strengthening of TRIUMF's mandate as a national infrastructure and technical support base for Canadian research in subatomic physics at facilities outside of Canada.

5. Establishment of a Canadian Nuclear Theory Centre.

Canadian nuclear theorists have made tremendous contributions to our understanding of all aspects of subatomic physics. In light of the vigorous program in experimental nuclear physics outlined in this document, we need to make sure that advances in nuclear theory and experiment continue to progress hand-in-hand. Many of the outstanding nuclear theorists in Canada have retired or are near retirement, and we need to sustain a vibrant theory community which includes young minds who can build upon theoretical advances of recent years. These efforts would be greatly facilitated by the establishment of a national Nuclear Theory Centre. Using the Jefferson Lab and BNL/RIKEN theory centres as models, one of the activities of the envisioned centre could be to advance the interests of nuclear theory nationwide and act as a catalyst for the continued health of the field.

3. Physics Case

3.1 Can we understand hadron structure and interactions in terms of QCD?

3.1.1 Overview

Quantum chromodynamics (QCD) is now firmly established as the fundamental theory of strong interactions. QCD is a theory of quarks and gluons whose properties and predictions at high energies (short distances) have been extensively tested experimentally. This is because in short distance interactions, the quark-quark interaction is relatively feeble (quark asymptotic freedom), so perturbative methods can be reliably applied to QCD. In contrast, in lower-energy (long distance) interactions, quarks and gluons are found to interact with one another exceedingly strongly. This leads to their confinement to form the building blocks of conventional matter, the protons and neutrons. In this regime, QCD calculations are enormously difficult and much less reliable. While the mechanism of confinement within QCD is understood qualitatively, a quantitative understanding of confinement remains "one of the greatest intellectual challenges in physics". A key component of this understanding is the question of hadron structure. For instance, can the properties of the nucleon, such as mass, spin, polarizabilities, charge and current distributions, be reproduced quantitatively in terms of the underlying quarks and gluons within the framework of QCD?

Considerable progress has recently been made on the theoretical front to address this outstanding problem. On one hand, the basic symmetries of QCD, primarily chiral symmetry, have been exploited to develop "effective field theories" capable of producing specific predictions of hadron structure and interactions at low energies (e.g., nucleon electric and magnetic polarizabilities and pion-nucleon interactions). Considerable progress is also being made to carry out detailed QCD calculations of hadron properties using a discretized space-time lattice. While these "lattice QCD" calculations were previously confined to the heavy quark sector, advances in computational techniques have recently allowed them to be applied to the light quark sector with greater authority. These calculations have great potential to revolutionize our understanding of QCD and allow precision predictions of hadron properties (e.g. quark electromagnetic form factors of the proton and pion form factor) to be made. It is gratifying to note that in both of these areas Canadian nuclear theorists are making valuable contributions and, in some instances, are leading their respective fields.

Experimentally, Canadian nuclear physicists are actively involved in a number of studies of hadron structure and dynamics using primarily electromagnetic probes at world-class facilities offshore, such as the Jefferson Laboratory (JLab) in the USA and the Mainz Microtron (MAMI) laboratory in Germany. These efforts follow a long tradition of Canadian leadership in hadron physics at TRIUMF and at the former Saskatchewan Accelerator Laboratory (SAL) using hadronic (proton, neutron, pion) or electromagnetic (electron, photon) beams. The long-term goal of the present experimental program can be broadly stated as the better understanding of hadronic structure in the non-perturbative regime.

3.1.2 Experimental program

Hadron structure with electromagnetic probes at JLab and MAMI
Priority: High
At JLab, a University of Regina group is involved in electron scattering studies aimed at measuring the electromagnetic form factors and spin structure functions of the proton as well as the π^+ electric form factor (F_π). In elastic scattering, where the space-like form factors are measured, quark effects in the hadronic system do not readily manifest themselves. However, this subject is of crucial importance, because it is where the most detailed tests of our understanding can be obtained. The Regina group has a leading role in many aspects of these measurements, but especially those of F_π. This form factor is rigorously calculable in perturbative QCD (pQCD), but the value of momentum transfer Q^2 at which F_π will take its pQCD value, as well as the actual behaviour of F_π as a function of Q^2 as QCD transitions smoothly to its non-perturbative (long-distance scale) confinement regime, are unknown. The pion is one of the simplest QCD systems available for study, and the measurement of F_π is our best hope of observing this transition experimentally. These measurements are carried out by studying pion electro-production from the proton and performing a longitudinal/transverse (Rosenbluth) separation over a range of Q^2. The first F_π results from these measurements have been published (see Figure 3-1) generating considerable interest. More data are being analyzed and plans are under way to extend the measurements to higher Q^2 following the JLab 12-GeV upgrade.

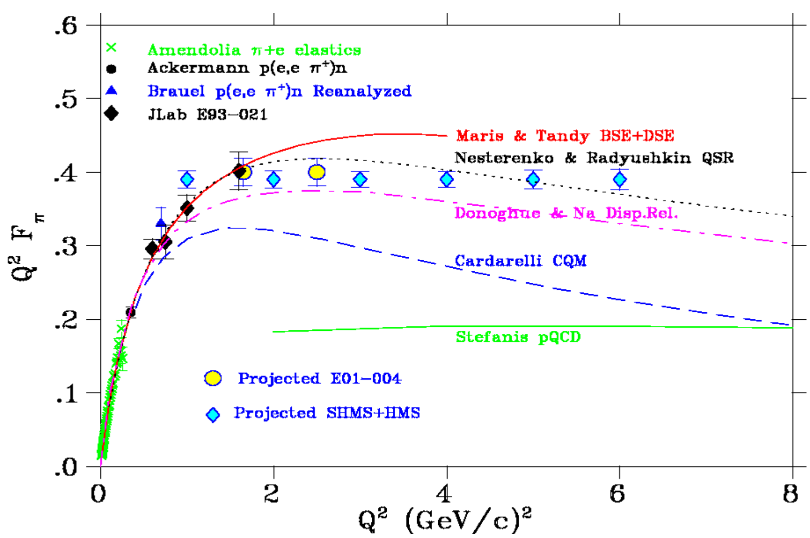

Figure 3-1: ***Current world and proposed Q^2F_π data and comparison with a number of QCD-based calculations of pion structure. The JLab 12-GeV upgrade (blue diamonds) will allow measurements through the expected transition region from confinement-dominated dynamics (modest Q^2) to perturbative-dominated dynamics (high Q^2).***

Another Canadian group from Saint Mary's University is involved in measurements of nucleon resonances (mainly the "Roper" resonance) at JLab, which are overtly sensitive to QCD confinement and potentially accessible to comparison to Lattice QCD calculations. This program also involves studies of the deuteron elastic form factor $A(Q)$ at low Q^2, and deuteron photo-disintegration and proton knockout reactions. These studies are directed toward exploring the limits of meson-nucleon models of the simplest nuclear system (the deuteron), with the intention of determining where such models break-down as the energy increases, and identifying where/how sub-nucleonic degrees of freedom manifest themselves in light nuclei. Many of these measurements utilize recoil-proton polarimetry to provide stringent tests of various models of nucleon excitation or deuteron structure. The future plan of this group at JLab is to pursue the study of nucleon resonance form factors following the JLab 12-GeV upgrade.

Photo-nuclear reactions are complimentary in nature to electron scattering reactions. A group at Mount Allison University is pursuing precision hadron structure studies using tagged photon beams at MAMI. One component of this program involves probing the structure of nucleon resonances (mainly the Δ and Roper); another utilizes threshold meson photo-production and Compton scattering off the proton and the deuteron to test predictions of chiral perturbation theory. The importance of these measurements is emphasized by the current availability at MAMI of a new 1.5-GeV polarized photon beam and a new frozen-spin target. The group's long-term plans also envision collaboration with other Canadian groups at JLab, especially after the 12-GeV upgrade.

In summary, the electron and photon scattering programs at JLab and MAMI are generating exciting new data and insights and providing new opportunities to test various QCD-based models of hadron structure at modest energy. The upcoming JLab 12-GeV upgrade will create further opportunities to explore QCD properties in this transition region between the confinement and asymptotic freedom regimes. The clear intention of the scientists involved in these projects to integrate their collaborative efforts in the future is strongly supported.

The G^0 experiment at JLab
Priority: High

Also at JLab, the "Manitoba group", comprising scientists from The University of Manitoba, the University of Winnipeg, TRIUMF, and the University of Northern British Columbia, has been involved in the G^0 experiment, aimed at measuring the weak form factors of the proton with the goal of determining the strange quark contribution to the structure of the proton. By combining the measured weak form factors with the relatively well known electromagnetic form factors of the proton and neutron at the same Q^2, the strange electric and magnetic form factors G^s_E and G^s_M can be extracted. This is done by measuring the parity violating asymmetry in elastic electron-proton scattering over a wide range of Q^2 from 0.1 to 1.0 GeV^2 using longitudinally polarized electron beams. The many major contributions of the Canadian group to G^0, made possible by the tremendous technical and infrastructure support of TRIUMF, have been crucial to the success of this high-precision parity violation experiment. The first G^0 results from the "forward-angle" part of the experiment were published recently (D.S. Armstrong *et al.,* Phys.

Rev. Lett. **95,** 092001 (2005); see Figure 3-2) generating great interest and renewed challenge to theory, especially lattice QCD. The "backward-angle" measurements, needed to fully separate $G^s{}_E$ and $G^s{}_M$, will be starting at JLab in 2006. These measurements required additional apparatus, which again relied on TRIUMF's vital role as a national infrastructure resource in support of offshore experiments.

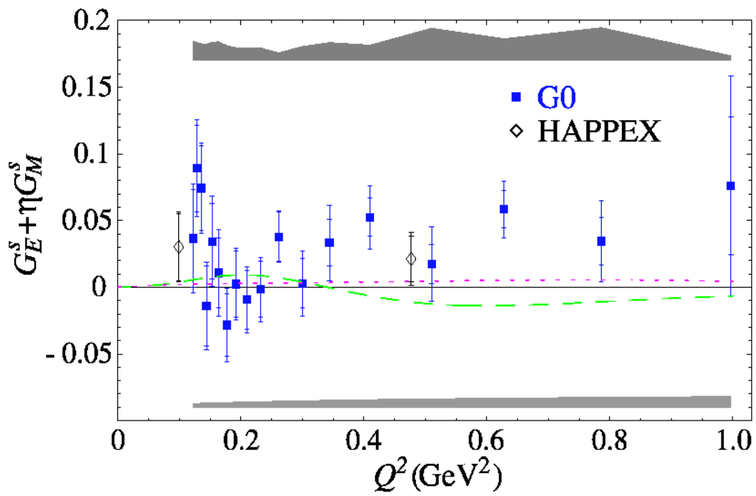

Figure 3-2: ***The linear combination of the two strange nucleon form factors $G^s{}_E + \eta G^s{}_M$ from the G^0 forward angle measurement. The upcoming backward angle measurement will allow the two form factors to be separated. The grey bands indicate systematic uncertainties; the lines correspond to different nucleon electromagnetic form factor models. Note that*** $\eta = Q^2 / 4M^2$.

Photonuclear studies at HIGS
Priority: Medium
Other studies of hadron structure and dynamics are being pursued by the University of Saskatchewan group (former SAL group), primarily at the High Intensity Gamma Source (HIGS) facility of the TUNL laboratory, USA. This group, notwithstanding its reduction in size since the closure of SAL, has invested heavily in the experimental infrastructure of HIGS using former-SAL resources. The group's scientific program at HIGS is a natural extension to the SAL program in the areas of nuclear Compton scattering, photodisintegration of the deuteron and other light nuclei, and threshold pion photo-production (possible after the upcoming energy upgrade at HIGS). The high intensities of polarized photon beams delivered by this unique facility should allow for precise measurements of such important quantities as the Gerasimov-Drell-Hern (GDH) sum rule on the proton and neutron, the proton and neutron electric and magnetic polarizabilities, and the low-energy amplitudes in neutral pion photo-production from the proton, quantities that have all been calculated within the framework of chiral perturbation theory.

***np*→dγ at LANSCE and SNS**
Priority: Medium
Scientists from the Manitoba group, with NSERC and TRIUMF support, are also members of the NPDGamma experiment, currently running at LANSCE (Los Alamos). This is an experiment to determine the weak pion-nucleon coupling constant h_π by measuring the parity-violating gamma ray asymmetry A_γ relative to the neutron spin direction when polarized cold neutrons are captured in liquid hydrogen. Because the *np* system is free of nuclear structure uncertainties, a measurement of this asymmetry with sufficient precision will provide a unique test of non-perturbative QCD. The relevant weak hadronic couplings depend on quark-quark correlations in leading order, which is qualitatively different from other low energy QCD tests. The experimental apparatus has been commissioned, but the expected asymmetry is very small. The experiment will benefit from its planned relocation to the newly-commissioned SNS (Oak Ridge) in 2008.

3.1.3 Long-range vision

Canadian researchers have played leadership roles in both theory and experiment in this important field. With respect to the long-term aim of QCD physics, to better understand the transition from meson-nucleon effective degrees of freedom at long distance scales, to quark-gluon degrees of freedom at short distance scales, further advances are required in both theory and experiment. Lattice QCD holds the promise to revolutionize our understanding of QCD as applied to a wide range of phenomena. The experimental program is built upon the long heritage of Canadian leadership in hadron physics, and provides significant scientific impact for a relatively modest investment of funds. Over the longer term, the 12-GeV upgrade of JLab in 2012 will provide important new data that are required to substantially advance our knowledge of hadronic structure, and much of the Canadian effort should be concentrated there. These efforts also include the Canadian contributions to the GlueX experiment at the upgraded JLab, which is an IPP-supported project with related physics goals.

3.2 What is the structure of nuclear matter, and what is the role of nuclei in shaping the evolution of the universe?

3.2.1 Overview

The question "*What is the structure of nuclear matter?*" is a central one and touches upon many different areas. As was stated in the introduction, a central goal of nuclear physics is to explain the properties of nucleons, nuclei and nuclear matter. Ultimately, it is desirable to attain this goal starting from an understanding of the nucleon-nucleon interaction based on QCD. However, the determination of the nucleon-nucleon interaction from QCD poses a severe challenge, and, given the complexity of the strongly interacting many-body system, it is unlikely that detailed properties for all but the lightest nuclei can be derived from an underlying nucleon-nucleon interaction.

It is in this context that nuclear models have been developed. These models are based on properties of nuclei located at or near the line of stability where basic data are available. However, the extrapolation into areas where no data exist is highly uncertain, and very often, once data do become available, the extrapolations turn out to be wrong. At this point there is no satisfactory answer to the question posed above. In order to make progress, we need to break the question down into smaller, more manageable questions. However, there is a clear path to develop the answer, by addressing the following questions:

i) What are the limits of nuclear existence?
ii) How do the properties of nuclei evolve as a function of the neutron-to-proton asymmetry?
iii) How do the properties of nuclei evolve as a function of proton and neutron number?
iv) What are the mechanisms responsible for the organization of individual nucleons into the collective motions that are observed?

The question "*What is the role of nuclei in shaping the evolution of the universe?*" is intimately related to the structure of nuclei and nuclear matter. The synthesis of hydrogen, helium, and lithium in the Big Bang is thought to be understood; elements heavier than this are predominately produced as a result of stellar burning, supernova explosions, and other astrophysical phenomena. It is a goal to understand fully the origin of the elements in the universe, and how nuclei impact directly the nature of the astrophysical objects and their dynamics. We cannot yet give a satisfactory answer to the question posed above. As before, we break this one central question down into manageable pieces that the Canadian SAP community is concentrating on:

i) How does stellar evolution proceed?
ii) How and where are nuclei heavier than iron created?
iii) What reactions are important to explain the γ-ray yields observed in the galaxy?

Nuclear structure and nuclear astrophysics, as broad fields of investigation, attempt to answer these questions. Nuclear structure and nuclear astrophysics are so intertwined that any separation between them is somewhat arbitrary and artificial. In order to explain stellar evolution, the mechanism of supernova explosions, the nature of neutron stars, etc., basic nuclear physics data such as half lives, masses, reaction rates, and nuclear equations of state are needed. Given the complexity of many of the reaction networks that are thought to be present in stellar burning and explosive nucleosynthesis, and the locations of the various process paths, which often occur very far from stability, it cannot be expected that all necessary data will be measured. Therefore, nuclear models must be relied upon at least partly. The development of accurate and *predictive* nuclear models, however, has proven to be a challenge for decades. The very nature of the strongly interacting many-body system does not lend itself to easy computation. Nuclear structure investigates the properties of nuclei in an attempt to understand their natures, and to guide the development of nuclear models such that they are able to accurately predict properties beyond the reach of experiment.

This part of the nuclear physics brief will focus on the plan of the Canadian subatomic physics community to address the fundamental questions outlined above. Rather than try an artificial separation into structure and astrophysics, we instead give a unified presentation that reflects their commonality.

3.2.2 Nuclear structure and nuclear astrophysics

This section concentrates on the physics that must be addressed in order to make progress on the larger questions.

What are the limits of nuclear existence?

One of the critical questions in nuclear physics concerns the limits of existence, i.e. at what point do nuclei become unbound? Not only is this question of profound importance in our understanding of the nature of the nucleonic system, but also has a deep impact on nuclear astrophysics, especially in connection to the nucleosynthesis of heavy nuclei through the *r*- or rapid-neutron-capture process. On the proton-rich side of the valley of stability, the position of the proton drip line has been delineated for many of the elements since this region can be accessed by stable beam/target experiments. On the neutron-rich side, however, the location of the neutron-drip line is unknown for all except for the lightest elements, up to oxygen. Shown in Figure 3-3 is chart of the nuclides indicating the known stable and unstable nuclei (coloured areas), as well as the regions where bound nuclei are predicted to exist but as yet have not been observed, the outer boundaries of which are labelled by B_p=0, B_n=0 and B_f=4 MeV.

The uncertainty in predicting the limits of nuclear existence is due to an incomplete knowledge of nuclear properties progressing away from the line of stability. All nuclear models use detailed properties of nuclei where they are known in order to determine the proper form of the effective interactions and their parameters. However, these effective interactions have been calibrated mainly with nuclei at, or near, stability.

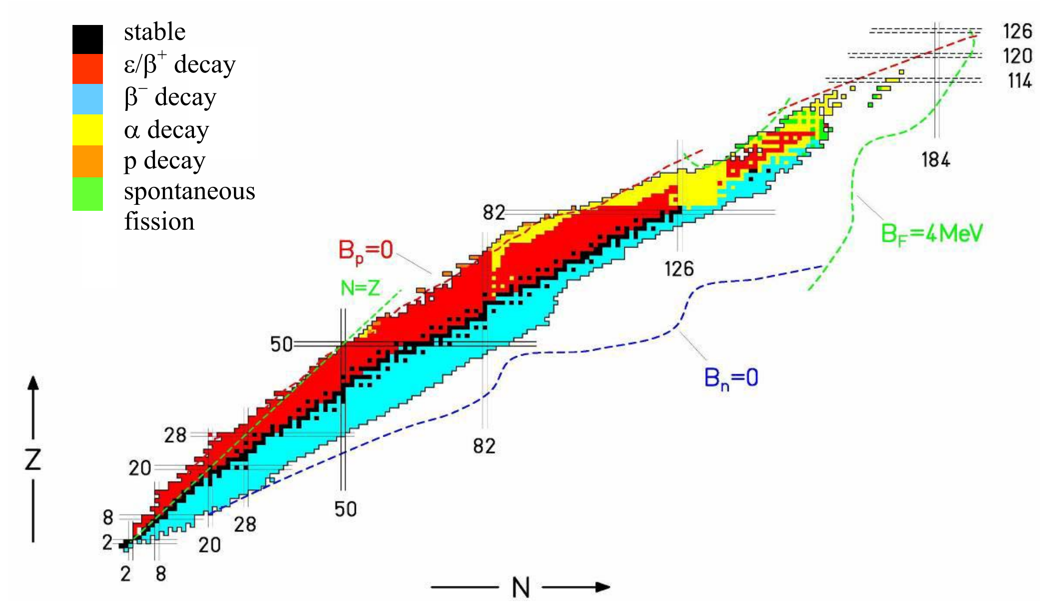

Figure 3-3: *Chart of the nuclides displaying the stable nuclei (black), and unstable nuclei with their prominent decay modes. The lines indicate where the respective binding energies of the last proton and neutron, are zero (labelled by B_p=0, B_n=0), and where the fission barrier drops to B_f=4 MeV, and hence instantaneous fission occurs. These three lines show the possible limits of existence. The limit is fairly well understood for proton-rich nuclei (those to the left of the stable nuclei), but on the neutron-rich side is not known beyond oxygen (Z=8).*

While all mass models reproduce the known experimental data reasonably well, extrapolating to the drip lines results in uncertainties that may reach 10 mass units. One of the main reasons for this is the interplay between the bulk, smoothly varying properties of nuclei and the structure of nuclear shells. The exact location of the proton and neutrons shells and whether these shells are open or closed can result in substantial change in the binding energy. Accurate and precise mass measurements on nuclei far from stability are needed in order to fix model interactions and parameters.

The Canadian community is addressing this question with experimental programs with the Canadian Penning Trap (CPT), in operation at Argonne National Laboratory in the US, and TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) being constructed at TRIUMF-ISAC. The Canadian component of the CPT collaboration includes the group from Manitoba and McGill, and the TITAN collaboration includes researchers from Calgary, Manitoba, McGill, TRIUMF, Windsor, and York. The CPT collaboration has already measured approximately 60 masses to high precision, and is having a major impact on the extraction of the V_{ud} matrix element with a highly precise measurement of ^{46}V and ^{46}Ti masses.

How do the properties of nuclei evolve as a function of the neutron-to-proton asymmetry?

Closely related to the question of the limit of nuclear existence is how the properties of nuclei evolve as a function of the neutron-to-proton asymmetry. New, sometimes completely unexpected phenomena appear in very neutron-rich nuclei. Light-mass nuclei that contain an excess of neutrons can form so-called 'halo' systems – nuclei where some of the valence neutrons have a spatial extent that greatly exceeds the expected nuclear dimensions. One of the first examples of this phenomenon was ^{11}Li. With 3 protons and 8 neutrons, its spatial extent is nearly that of the much more massive ^{208}Pb. In ^{11}Li, the halo is comprised mainly of two weakly-bound neutrons. Removal of one neutron results in the unbound nucleus ^{10}Li, indicating that it is the extra pairing energy of the valence neutrons that is responsible for the additional binding energy for the existence of ^{11}Li. It has been proposed that the extra pairing strength is mediated by the exchange of low-frequency surface vibrational modes of the nucleus, and confirmation of this mechanism would lead to the understanding of the ^{11}Li halo as an isolated neutron Cooper pair. These systems thus provide an ideal tool for understanding the origin of the collective pairing interaction in nuclei that manifests itself as superconductivity in heavier systems. The Canadian community has already had an impact here by providing evidence that, with an experiment with the 8π spectrometer at TRIUMF-ISAC, the halo-neutron structure can survive the process of β decay. Heavier nuclei, rather than forming halos may instead form neutron skins, and new phenomena, such as the soft "pygmy" resonance mode, where the skin oscillates against the rest of the nuclear fluid, are expected. The reaction rates of nuclei with skins are expected to change, as well as their decay properties. Measurements of the β decay, transition matrix elements, and the determination of reaction rates are needed in additional halo nuclei and neutron-skin nuclei. Further, the establishment of the thickness of the skin, determined by examining the difference between the nuclear matter radius and the charge radius, is a crucial quantity for testing models of nuclear matter.

One very important aspect of the proton-neutron asymmetry concerns the nuclear equation of state (EOS). The static and dynamic behaviour of stars is determined to large extent by the nuclear EOS, and potential phase transitions may occur in the nuclear matter found in neutron stars and supernovae. The asymmetry term in the EOS can be determined by studying nuclear-reaction products where there is a large variation in the proton-neutron asymmetry, and requires experiments where the reaction products are analyzed as a function of the beam energy and neutron-to-proton asymmetry in the collisions.

The Canadian community is addressing this question with experiments being conducted or planned at TRIUMF-ISAC/ISAC-II using the 8π and TIGRESS γ-ray spectrometers, the TUDA facility, and the HÉRACLES spectrometer. Following on the initial success of studies at TRIUMF-ISAC by the 8π collaboration using a ^{11}Li beam, future investigations in this direction are planned with a β-decay experiment on ^{14}Be. As additional ion sources and targets come on-line, it will be possible to extend these investigations into heavier nuclei probing additional examples of haloes and neutron skins. The high-energy ISAC-II beams will enable direct studies of the halo-nucleon wave functions through 1 and 2-particle transfer reactions. Halo states in

^{12}Be, for example, will be populated and studied in the d(^{11}Be,pγ)^{12}Be reaction with TIGRESS at ISAC-II. The intense ^{11}Li (> 10^4 ions/s) beam now available at ISAC will also be used to study pairing correlations between the two halo neutrons with TUDA using the ^{11}Li(p,t)^{9}Li reaction and via neutron pair transfer reactions on heavy targets. The first project to be performed with HÉRACLES at TRIUMF/ISAC-II consists of using the projectiles ^{20,24,26,28}Na on ^{12}C and ^{24}Mg targets between 8 MeV per nucleon to 15 MeV per nucleon. The multidetector array HÉRACLES will be operated for the detection of all charged particles and fragments of each collision in a manner as complete as possible. For the first series of experiments, in one projectile-target system, neutron energy will also be measured.

To measure the thickness of the neutron skin, precision laser spectroscopy will be performed. Laser spectroscopy measures very precisely the transition energies between atomic levels, and thus is sensitive to the hyperfine interaction. The hyperfine interaction is the coupling between the atomic electrons and the nucleus. Therefore, precision atomic spectroscopy can yield detailed information on ground and long-lived isomeric state nuclear spins and moments. When these are carried out at radioactive beam facilities, where long chains of isotopes of many elements are available for study, systematics of the change in the mean squared charge radii as well as the radial distribution of valence neutrons can be deduced. Knowledge of the nuclear matter radius, deduced from analysis of nuclear reactions, provides a consistency check and gives confidence in the extracted value of the neutron-skin thickness. In a effort led by a GSI group using ISAC's uniquely large ^{11}Li production, precision laser spectroscopy has measured the ^{11}Li charge radius to be much larger than that of ^{9}Li, providing a measurement of the halo's perturbation of the core

How do the properties of nuclei evolve as a function of proton and neutron number?

This question underlies all other questions in nuclear structure, and also has a major impact on nuclear astrophysics. To a very large extent the question of the evolution of nuclear properties with proton and neutron number can be recast as the question “How does the nuclear shell structure evolve with proton and neutron number?” The limits of bound nuclei are intimately connected with the properties of nuclear shells – their locations and nature as a function of proton and neutron number. The location of shells also determines how the organization of nucleons into collective behaviour manifests itself – whether at low excitation energy the nucleus behaves like a few particles orbiting a closed inner core, if it acts similar to a quantum vibrational system, or if it acts more like a quantum rotor. A number of theoretical calculations predict that the familiar shell gaps that give rise to the “magic” numbers, or major shell closures, may change drastically in neutron-rich nuclei. Shell structure has a major influence on the limits of bound nuclei, and is a very important ingredient in nuclear masses. Figure 3-4 shows one possible scenario, based on theoretical calculations, for how shell structure *may* be modified in very neutron-rich nuclei. The locations of the nuclear shells as a function of both proton and neutron number are critical data for testing and refining nuclear models – models that have had their parameters tuned from knowledge of nuclei on or near the line of stability. The locations of shells also has a profound impact on nucleosynthesis models, through their influence on nuclear masses and hence on the location of the *r*-process path, and also on the nature of the excited levels (and the density of them) through which reactions, like (n,γ) and (p,γ), proceed.

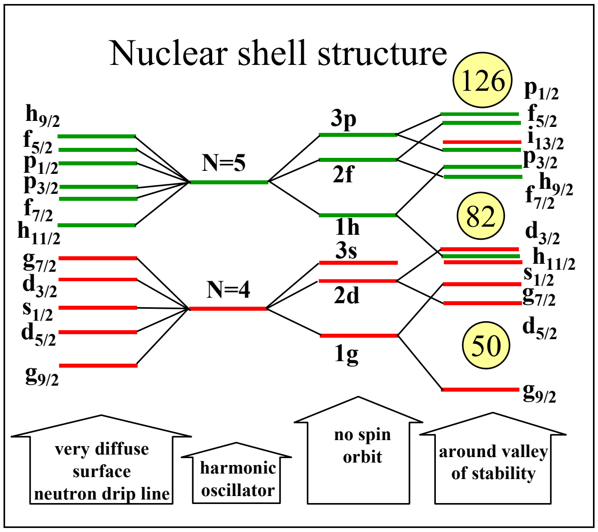

Figure 3-4: *Shell structure as observed around the valley of stability (right), and that predicted for very neutron-rich nuclei. In order to probe shell structure, experiments such as transfer reactions, or those designed to extract transition matrix elements like coulomb excitation or lifetime measurements must be performed. For definitive results, systematic studies following the evolution of shell from stability are needed.*

Shown in Figure 3-5 are derived *r*-process abundances compared with results of calculations based on two different assumptions; the purple curve are the predicted abundances using knowledge of shell structure derived from the line of stability, and the red curve assuming that the major shells are "quenched", as shown in left side of Figure 3-4. As can be seen, there is nearly a two-orders-of-magnitude increase in the calculated abundance of elements near mass 120 as a result of the *N*=82 shell being quenched. This demonstrates the interconnectedness between nuclear structure and nuclear astrophysics, and in this particular case the modification of shell structure was called for from astrophysics before any evidence from nuclear structure studies was found. However, it is not yet certain if the shell structure is indeed modified, or if the astrophysical model is wrong. A major line of research, by many groups worldwide, is the mapping of the nuclear shells as one proceeds away from stability.

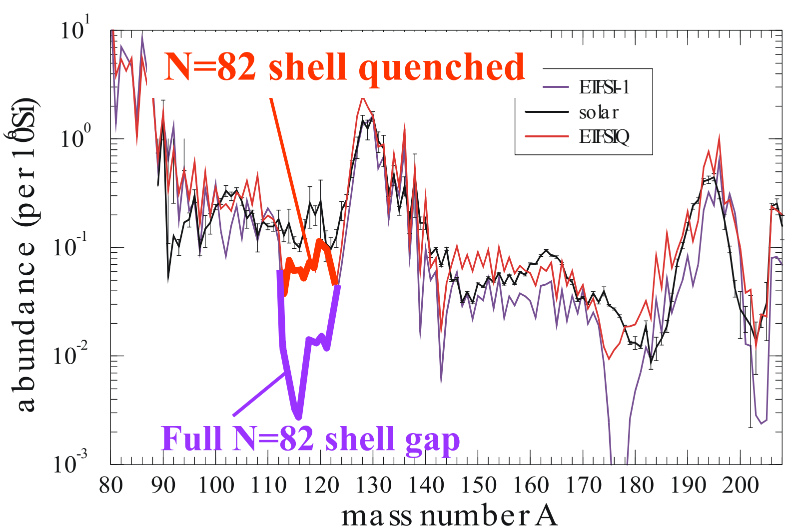

Figure 3-5: *r-process abundances predicted using modes with (red) and without (purple) quenching of the N=82 shell below ^{132}Sn. This example demonstrates the impact of nuclear structure on the understanding of the observed elements in the universe.*

In order to determine the evolution of the nuclear shells, systematic investigations must be performed starting from nuclei near stability, where the location and nature of the shells are well determined, and progress outwards towards the limits of existence – the *drip lines*. In order to map shell structure, extensive systematic studies of nuclear properties must be performed starting with nuclei near the stability line, where the locations of the shells are, in general, known, and progressing outwards. There are several key experiments which must be undertaken: 1) mass measurements, where evidence for major shell closures are found in deviations of the masses from smooth trends; 2) β-decay studies, that often yield the first crucial information on the locations, angular momenta, and parities of excited states and isomers, and test key selection rules related to the underlying nature of the levels; 3) Coulomb excitation, measurements that determine key matrix elements depending on the state wave functions, specifically the collective properties; 4) single-nucleon transfer reactions that probe the microscopic (single-particle) nature of state wave functions, and; 5) nuclear radii measurements via precision laser spectroscopy. The Canadian community is planning to use all of these tools to access shell structure evolution with a number of experiments using TITAN, the 8π and TIGRESS spectrometers, and EMMA.

Firm experimental evidence for the drastic change in shell structure as a function of proton and neutron number has been obtained in the neutron-rich oxygen and nitrogen nuclei where the familiar N=20 shell disappears, and the N=16 shell gap appears instead. This may be related to a proton-neutron interaction not previously considered in theoretical calculations. The exact mechanism, however, is not yet fully understood, nor is the region fully delineated where the change occurs. In order to address these questions, experiments using β-decay observed with the 8π spectrometer will be performed on neutron rich nuclei near ^{32}Mg. Initial TIGRESS experiments will focus on measuring precisely *E2* transition matrix elements using Coulomb excitation for the $N = 16$, and $N = 18$ isotopes ^{26,28}Ne. When intense beams of the most neutron-rich nuclei become available from the ISAC actinide target, these studies will be extended to ^{30}Ne and ^{30,32}Mg.

The next horizons to explore the evolution of shell structure are in the Ca and Ni region, and in the Pd, Cd, and Sn region. New theoretical calculations incorporating interactions thought responsible for the modification in shell structure have become available, and provide the motivation for these experimental tests. For example, for slightly neutron-rich Ca isotopes the increasing energy of the $f_{5/2}$ orbital is thought to generate a new magic number at N=34, making ^{54}Ca a doubly-magic nucleus along with its stable partners ^{40}Ca and ^{48}Ca. As of yet the data do not exist to test this prediction. The seniority isomer also gives important structural information regarding the seniority isomer. These isomers arise in "shell-model" nuclei, i.e. those that are sufficiently close to closed shells that they can be described quite well by a few valence nucleons orbiting the closed core. The isomer arises when the maximum amount of angular momentum that can be created in a simple configuration is reached; as this point is approached, the level spacing decreases and the level lifetime become very long. The existence of seniority isomers is thus a measure of the degree to which closed-shells remain closed; an easily-broken core causes structural changes that destroy the few-particle natures needed to form seniority isomers.

The hypothesis of a new magic number at N=34 will be tested through Coulomb excitations of neutron-rich ^{50,52,54}Ca and ^{48,50,52}Ar beams with TIGRESS. At still heavier masses, seniority isomers in the neutron-rich $A=80$ region will be sought, and the validity of the N=50 shell gap at large neutron excess will be probed through Coulomb excitation studies in the vicinity of ^{78}Ni, while on the proton-rich side of the valley of stability *E2* transition matrix elements of neutron-deficient Sn isotopes approaching ^{100}Sn, the last proton-bound doubly-magic *N*=*Z* nucleus will be measured. In the longer-term, when 12 TIGRESS detector modules are available and ISAC-II has reached its full energy capability (2009), detailed studies of nuclear shell structure will be extended to include fusion-evaporation reactions populating excited states in nuclei around ^{32}Mg and ^{100}Sn, and deep inelastic reactions with radioactive beams such as ^{81}Ga to populate high-spin states in nuclei around ^{78}Ni. Many of these experiments will need, or be greatly enhanced by EMMA.

The very high mass resolution of the EMMA spectrometer makes it the ideal device for an extensive program of (d,pγ) transfer reactions in conjunction with TIGRESS for γ-ray detection and a segmented Si array for coincident proton detection. The case of d(^{132}Sn,p)^{133}Sn is the archetypical experiment of this type and EMMA has been designed to cleanly resolve the transfer products from beam particles with > 10^6 higher intensity. An extensive program of such inverse (d,pγ) studies at ISAC-II will map the evolution of single-particle states as a function of neutron excess and, in particularly favourable cases such as d(^{100}Rb,pγ)^{101}Rb, will be performed on the *r*-process nuclei themselves. As the primary surrogate for the study of (n,γ) capture reactions, such (d,pγ) studies with TIGRESS, EMMA, and the 4π Si array will form the centrepiece of the ISAC-II physics program and will establish ISAC as the world leader in this field. Systematic mass measurements with TITAN and CPT will also reveal the presence of closed shells by locating discontinuities identifying nuclei with "extra binding". These will provide important complementary data to that obtained with γ-ray studies.

Future plans also call for the installation of a high-precision laser spectroscopy facility at TRIUMF for measurements of isotope shifts, or changes in nuclear radii, that are also sensitive to the locations of shells.

What are the mechanisms responsible for the organization of individual nucleons into the collective motions that are observed?

In many complex systems, simple patterns may emerge. In nuclei, which may contain hundreds of individual nucleons, rather than displaying chaotic energy spectra they often show remarkably simple excitation spectra at low energies. The emergence of the simple patterns is often related to underlying symmetries in the Hamiltonian. The phenomenon of pairing, discussed in the context of the neutron halo above, is one example of this. It is well known that *T*=0, *S*=1 is the strongest channel of the nucleon-nucleon force. However, the pairing field appears to be dominated by collective *T*=1, *S*=0 pairs, rather than *T*=0, *S*=1 pairs, even in *N*=*Z* nuclei where the latter might be expected naively to play a more dominant role. In heavy nuclei, a collective *T*=1 pairing field develops that eventually forms a superconducting state.

Nuclei also organize (approximately) into different shapes, and may possess surface vibrational modes. Spherical even-even nuclei away from closed shells are often labelled as vibrational, since their low-lying spectrum can resemble that of a simple harmonic oscillator, while deformed nuclei are labelled as rotational since their spectrum resembles that of a quantum rotor. While models can account for these modes with some reasonable degree of success, a long-term challenge has been the transitional regions where the shape undergoes a rapid change. For many years it has been known that nuclei near N=90, for example, exhibit a rapid change in the shape of the ground state as the neutron number increases from N=88 to N=92. Early work, based on two-nucleon transfer reactions, suggested that nuclei in this region exhibited shape coexistence. Very recently, a new interpretation was put forth that nuclei at N=90 are at a *critical point* of a shape *phase transition*. New theoretical models have been developed based on *critical-point symmetries*. It has been claimed that these new models successfully describe the level structures of a series of many transitional nuclei; however, the lack of precision data prevents definitive conclusions. These results have given a strong impetus for many groups to search for other examples of critical phenomena in nuclei, and for the development of the idea of critical-point symmetries. Most of the candidates for critical phenomena are located away from the stability line, necessitating the use of radioactive beams for their investigation. A program has been initiated to provide a definitive answer between the alternative descriptions of the N=90 isotones as having shape coexistence, or providing an example of a quantum shape phase transition. Studies to date with the 8π spectrometer include ^{156}Ho and ^{158}Tm decay, and future measurements in other N=90 isotones are planned. Regions of shape coexistence also include the neutron-deficient Pb and Bi isotopes. While shape coexistence has been established in these nuclei, it is based on incomplete data; conclusive proof rests in the measurements of enhanced *E0* transitions.

The $N \approx Z$ nuclei in the region of ^{68}Se – ^{74}Rb display rapid changes in structure associated with the coherent effects of proton and neutron wave functions and Coulomb excitation with TIGRESS at ISAC-II of nuclei such as ^{68}Se, ^{70}Br, ^{72}Kr, and ^{74}Rb will probe shape co-existence in this region. The odd-odd N=Z nuclei provide excellent candidates to study isospin-purity in these proton-rich systems, and pair transfer reactions such as ^{3}He(^{72}Kr,p)^{74}Rb will probe neutron-proton pairing correlations in these symmetric systems. Making use of a proposed new 4π CsI(Tl) charged-particle detector array and a neutron detector array for TIGRESS to efficiently select reaction channels, fusion-evaporation reactions with radioactive beams such as ^{40}Ca(^{31}S,2αp)^{62}Ga, ^{40}Ca(^{34}Ar,2pn)^{71}Kr, ^{58}Ni(^{26}Si,αpn)^{78}Y, and ^{58}Ni(^{37}K,p2n)^{92}Pd will be used to probe high-spin states in heavy $N \approx Z$ nuclei, while the ^{13}C(^{22}N,p2n)^{32}Mg and ^{13}C(^{51}K,p3n)^{60}Cr will be used to study high-spin states in extremely neutron-rich systems. Deep inelastic reactions with beams such as ^{81}Ga, ^{94}Kr, and ^{97}Rb impinging on ^{208}Pb or ^{238}U targets will efficiently populate even more neutron-rich systems and allow for studies of nuclear shell structure and deformation in the extremely neutron-rich N=50 and N=60 regions of the chart of the nuclides.

Since many nucleons participate in the development of collective phenomena, the question naturally arises if there is a saturation effect. Nuclei near the mid-shell, that have the maximum number of valence protons and neutrons, would be expected to have the maximum collectivity. One may thus expect that a nucleus like ^{170}Dy, with Z=66 and N=104, would have the greatest degree of deformation. However, the lighter Gd isotopes have a greater deformation than their Dy isotones, prompting the idea that there could be a saturation effect. Experiments with the 8π spectrometer will investigate this by performing measurements to determine low-lying level schemes and lifetimes in the neutron-rich Gd and Dy isotopes.

Nuclei with well-deformed shapes typically possess a symmetry axis, and the projection of angular momentum onto this symmetry axis is the K quantum number. The degree to which K is conserved, i.e., the “goodness” of this quantum number, gives a direct indication of the nuclear shape, and mixing effects, such as the Coriolis force. The most sensitive way to probe the degree of violation of *K* is the measurement of the decay of *K* isomers. These isomeric states result from a unique combination of single-particle orbitals that lie relatively low in excitation energy and that have large spin components projected onto the symmetry axis. One of the best regions of the nuclear chart to investigate *K* isomers is the mass 170 – 190 region. A search using the 8π spectrometer for high-K isomers in the neutron-rich Hf, Tm, and Lu isotopes will continue once the actinide target is available, with the ultimate goal of discovering the long-lived K=18$^+$ isomer in ^{188}Hf.

The main tool for these studies is γ-ray spectroscopy with the 8π and TIGRESS spectrometers, the latter in conjunction with EMMA. The Canadian community, namely the 8π and TIGRESS collaboration, is heavily involved in the study of collective motions in nuclei and has a long history of world-leading research in this area.

How does stellar evolution proceed?

Stars evolve according to their mass and their initial chemical composition. When matter is compressed and heated by gravity, reactions that have the smallest Coulomb barrier will be the first to be initiated. Because the bulk of the matter in the universe is made of protons and helium, burning processes in a star will start with proton capture reactions. Depending on the mass of the star these will be the pp-chain, using nothing but protons, and the CNO cycle, requiring initial catalytic CNO elements. The timescale for the pp-chain is set by the weak-interaction reaction $p+p \rightarrow d+e^{+}+\nu$, while the timescale for the CNO cycle is set by the ^{14}N(p,γ)^{15}O reaction. The dividing line where the CNO cycle becomes dominant is slightly above one solar mass. Stars spend most of their lifetimes burning hydrogen.

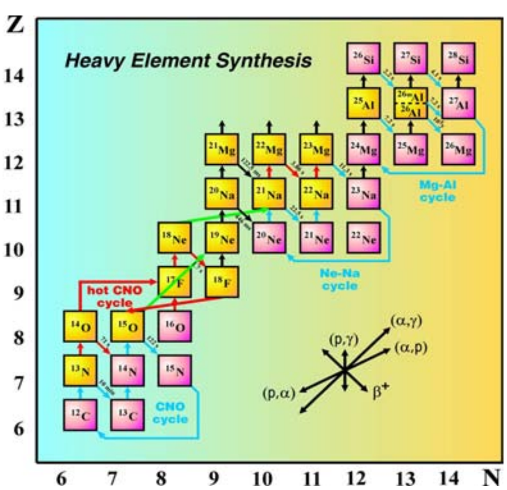

Figure 3-6: *Reaction network showing the CNO cycle, the hot-CNO cycle, the Ne-Na cycle, and the Mg-Al cycle. Important breakout reactions are the ^{13}N(p,γ)^{14}O, the ^{14}O(α,p)^{17}F, the ^{15}O(α,γ)^{19}Ne, and the ^{18}Ne(α,p)^{21}Na reactions.*

When the hydrogen in the centre of the star is burned, hydrogen burning will continue in a shell around this ever increasing He core and the star will inflate to become a red giant. The helium core will eventually contract and ignite by the 3α and ^{12}C(α,γ)^{16}O reactions, a process known as helium burning. The latter reaction has a complicated mechanism at the relevant energies and needs better understanding. After helium burning, stars of less than eight solar masses will become white dwarfs whereas stars more massive will commence heavy-ion burning. As the available energy from fusing lighter nuclei into heavier ones is exhausted, nuclear statistical equilibrium is reached where there is equality between the proton and α-particle photodisintegration reactions, and corresponding capture reactions. (It is in this phase that long-lived isotopes like ^{44}Ti and ^{60}Fe are produced, both detected galactic γ emitters.) Eventually the core of a massive star will collapse to a neutron star in a cataclysmic type-II supernova, which may be the site of heavy element production via the rapid (*r*) neutron-capture process. A reaction like ^{8}Li(α,n)^{11}B, to be measured by TACTIC, is important in this context for the determination of the mass flow to heavier elements.

Binary systems of stars are very common and can exhibit more complex evolution, in particular if the two stars are close and there is mass flow between the two. This leads to explosive events, if one of the partners is a dense star like a white dwarf or a neutron star. In the first case either a type-Ia supernova or a nova event will result, depending entirely on mass flow and closeness to the Chandrasekhar limit. SNIa are used as standard candles in cosmology. The ^{12}C+^{12}C reaction controls the initial ignition and will be the subject of a TACTIC experiment. If the dense object is a neutron star, explosive events known as type I X-ray bursts will happen. Reactions on the isotopes in the CNO cycle will produce most of the energy initially, however, in the case of X-ray bursters, feeding of isotopes into the CNO region via the 3α reaction as well as break out reactions from the CNO region such as ^{14}O(α,p)^{17}F, ^{17}F(p,γ)^{18}Ne, ^{15}O(α,γ)^{19}Ne, and ^{18}Ne(α,p)^{21}Na will occur. DRAGON will be used to measure the radiative capture reactions, while TUDA will measure those reactions with only charged particles is in the exit channel. Just above the the CNO region are the elements from neon to aluminum, connected to each other by the NeNa and MgAl cycles, where the galactic γ-emitters ^{22}Na and ^{26}Al are produced and destroyed via (p,γ) capture reactions. DRAGON has measured the important ^{21}Na(p,γ)^{22}Mg reaction. Figure 3-6 shows the CNO, Ne-Na, and Mg-Al cycles along with some of the important breakout reactions.

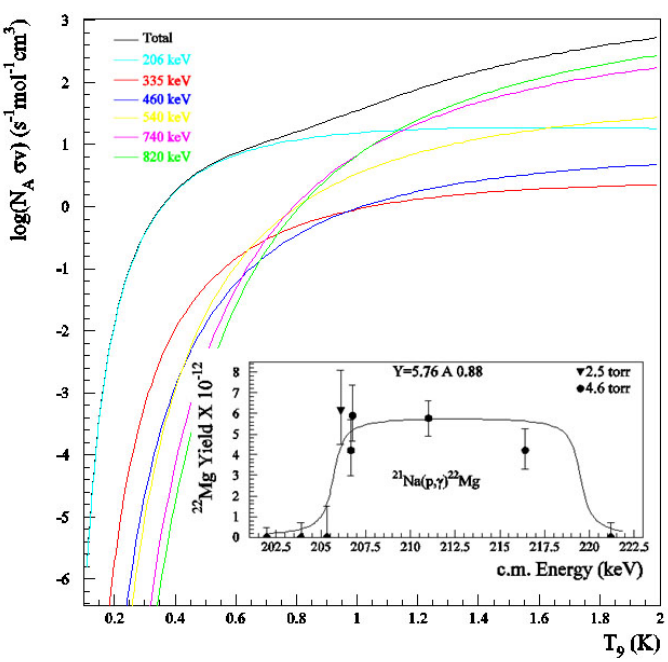

Figure 3-7: *^{21}Na(p,γ)^{22}Mg reaction rate resulting from the comprehensive DRAGON study of all known low-energy resonances. The inset shows the measured thick target excitation function for the 206 keV resonance, which dominates at nova temperatures.*

In order to understand the energy generation in stars and explosive environments, the Canadian community has focused on measurements to understand the nature of the resonances in nuclei involved and also focused on direct measurements at ISAC and ISAC-II. The DRAGON and TUDA facilities will be performing extensive measurements on the nuclei involved in the CNO and hot-CNO cycles. In light mass nuclei, the level density is low enough that the reactions take place via isolated resonances. In order to measure the reaction rate, the resonances must be identified, their spin/parity determined, and the quantity $\omega\gamma \propto \Gamma_p\Gamma_\gamma/\Gamma_{tot}$ measured. While DRAGON and TUDA facilities perform experiments that probe the reaction rates directly, other experiments aimed at improved spectroscopy will be undertaken. These include the (^{6}Li,d), and (^{3}He,p) reactions, and level spectroscopy of nuclei in this region may also be studied in the future via γ-ray spectroscopy with TIGRESS and EMMA.

How and where are nuclei heavier than iron created?

As the normal evolution of massive stars comes to a finish, they end their life in a spectacular explosion – a supernova. The explosion is one of the most energetic events in the universe, and releases the products of nucleosynthesis back into space. The mechanism for the explosion is not yet fully understood, and neither is it known what amount of material is ejected. However, supernovae are believed to be important sites for enriching the universe with heavy nuclei and they are candidates for the *r*-process site. The *r*-process, a series of rapid neutron captures, is responsible for approximately ½ of all nuclei heavier than iron. (Another substantial portion originate from the slow-neutron-capture, or *s*-process. Neutron-capture cross section measurements are of importance here, but the Canadian community is not involved in these. However, in a few cases, there are important structural effects that result in a branch point, or a bifurcation, of the *s*-process flow; the Canadian community is involved in the investigation of this effect in selected nuclei.) It requires extremely high neutron densities, temperatures, and the presence of "seed" nuclei. However, the exact location of the *r*-process path is very uncertain because of incomplete nuclear physics. Data on neutron-rich nuclei are desperately needed to constrain astrophysical models. These constraints will help determine the conditions, and hence the site, of the *r*-process. While it is generally true that knowledge of the (n,γ) reaction rate is unnecessary for the *r*-process, since there is an equilibrium between the (n,γ) and (γ,n) reactions, at the late stages the equilibrium is broken and knowledge of certain (n,γ) reactions becomes important since they affect the observed abundances. These particular reactions on nuclei on the *r*-process path are impossible to perform. However, important information on the reaction rate can be obtained from the (d,pγ) reaction.

As was explained above, nuclear shell structure has a tremendous impact on the location of the *r*-process pathway. The nuclear astrophysics of the *r*-process is the nuclear structure of neutron-rich nuclei.

Another important process that can occur in explosive nucleosynthesis is the rapid-proton-capture, or *rp*-process. This process begins with seed nuclei produced in the CNO cycle, and proceeds via the breakout reactions described above. The endpoint of the *rp*-process is still not well determined, but there is evidence that it proceeds to A>100, up into the Te region. The site of the *rp*-process is not yet known, but candidates include novae explosions, X-ray bursters, and shock fronts in type-II supernovae. The pathway is characterized by the so-called "waiting-point" nuclei, where the (p,γ) reaction cannot proceed (typically due to the product being unbound) and must await a β-decay before reaching a successful target for the subsequent (p,γ) reaction. Measurements of the (p,γ) reaction rate, masses, and β-decay lifetimes on the *rp*-process path are important.

The Canadian community is directly involved in the *r*-process investigation through studies of neutron-rich nuclear structure, with the TIGRESS and EMMA spectrometers, and the determination of nuclear masses with the TITAN and CPT facilities. Investigations of *rp*-process path nuclei will be performed using the 8π spectrometer; TIGRESS in conjunction with EMMA to study the nature of the nuclei involved; TITAN and CPT to determine masses; and TUDA and DRAGON to locate and measure resonances directly.

What reactions are important for the yields of decay γ rays observed in the galaxy?

A new generation of γ-ray observing satellites has made impressive maps of the γ-ray distributions in the galaxy. Decay γ rays from ^{26}Al and ^{44}Ti have been observed, whereas those from ^{22}Na have not, in contradiction with reaction network models that produce it in sufficient quantity. These distribution maps contain a wealth of information on the nuclear processes, and hence astrophysical environments. However, in order to be useful, key reaction cross sections involved in the production and destruction of the parent nuclei must be known. The most important reaction for the net production of ^{22}Na, ^{22}Na(p,γ)^{23}Mg, will be probed directly with DRAGON. It is believed that the reactions ^{26g}Al(p,γ)^{27}Si, ^{25}Al(p,γ)^{26}Si, ^{26m}Al(p,γ)^{27}Si, and ^{23}Mg (p,γ)^{24}Al reactions are the most important for the net production of ^{26}Al. The nuclide ^{44}Ti has been described as one of extraordinary astrophysical significance. There is a relatively large abundance of ^{44}Ca (2'nd in the Ca isotopes and 44th most abundant in the solar system) due primarily to synthesis of ^{44}Ti parent. ^{44}Ti has been observed directly in a supernova remnant (Cas A), and in the light curve of SN1987A, with more observations are likely in the near future, and ^{44}Ca enriched meteorites have been identified as pre-solar particles that condensed from supernovae ejecta. However, the key rate for the production of ^{44}Ti via the ^{40}Ca(α,γ)^{44}Ti reaction is unknown. This important reaction will be studied with the DRAGON spectrometer.

3.2.3 Experimental equipment needed to address the science questions

In this section, we describe the capital equipment that the Canadian SAP community is using to address the science questions laid out above, together with priorities. Most of this work will be conducted at the TRIUMF ISAC and ISAC-II radioactive-beam facilities. TRIUMF is a world leader in radioactive ion beams (RIB's), and currently has the highest-power targets used for radioactive beam production. With unique (or planned) and world-leading instruments, like DRAGON, the 8π Spectrometer, TIGRESS, TUDA, TITAN, EMMA, etc., radioactive-beam physics conducted at TRIUMF is on the leading edge. Not only does the bulk of the Canadian community perform its research at TRIUMF, but also the facility attracts a large number of international collaborators, from the U.S., Europe, and Asia, many of whom choose TRIUMF over their own national RIB facilities. It must be emphasized that large components of the research programs described here depend critically on the availability of new, and sometimes very intense, beam species at ISAC through ion source and target (especially actinide target), development.

Mass measurements using CPT and TITAN
Priority: Operating – High
New Capital – Medium

The mass of the nucleus is one of its basic properties, and provides critical data for nuclear structure, astrophysics, and weak interaction studies. The Canadian community is involved in two main mass-measuring experiments: the Canadian Penning Trap (CPT) located at Argonne National Laboratory in the US, and TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) being constructed at TRIUMF-ISAC. The CPT is currently online and has measured approximately 60 masses thus far. TITAN is a multi-ion-trap system installed at the radioactive ion beam facility ISAC. The uniqueness of the system lies in the combination of different kinds of ion traps, a combination nowhere else available, and in particular the utilisation of highly charged ions, which allows to boost the precision by an order of magnitude. In 2002, a Major RTI award for three years ($1.93 M) was given to the TITAN collaboration to build this facility. TITAN consists of four (with a later upgrade, five) main components; 1) a gas-filled linear radio-frequency quadrupole (RFQ) ion trap, for cooling and bunching the radioactive beam, 2) an electron-beam ion trap (EBIT), for charge-stage boosting, 3) a Wien-filter for selecting a specific mass-to-charge ratio, 4) a Penning ion-trap for mass determination, and finally 5) a cooler-Penning-ion trap, between EBIT and Wien-filter, for beam quality enhancement. Both the TITAN and CPT facilities offer the possibility of very-high precision mass measurements, to better than 10^{-8}. They are complementary in that the CPT traps ions that are produced by reactions at the ATLAS accelerator, and therefore is insensitive to chemistry (and no ion sources are needed), whereas TITAN uses the ISOL source, that populate a larger but different region of the chart of nuclei. In particular TITAN will be able to perform measurements on neutron-rich nuclei once the actinide target at TRIUMF comes online. (CPT can reach some of these through the use of a ^{252}Cf spontaneous fission source.)

The TITAN collaboration currently consists of 14 NSERC eligible researchers from TRIUMF, Manitoba, McGill, Windsor, Calgary, and York. The Canadian component of the CPT collaboration consists of 6 NSERC eligible researchers from Manitoba and McGill. Of note are 3 new hires within the past 5 years who work on ion trap systems.

γ-ray spectroscopy with the 8π and TIGRESS
Priority: Operating – Very High
New Capital – High/Medium

The 8π and TIGRESS spectrometers at TRIUMF-ISAC/ISAC-II are used to study the γ radiation emitted following radioactive decay, Coulomb excitation, direct reactions, fusion-evaporation reactions, etc. The 8π spectrometer and its associated auxiliary detectors is the world's most powerful device devoted to radioactive decay studies. It consists of 4 different detector systems: 20 Compton-suppressed HPGe detectors (the 8π) for γ-ray detection, 20 plastic scintillators (SCEPTAR) for detection of β particles, 10 BaF_2 detectors (DANTE) for γ-ray detection for fast-timing measurements, and 5 Si(Li) detectors (PACES) for conversion electron spectroscopy.

Complementing these is an in-vacuum tape-transport system for the removal of long-lived activities, and the ability to precisely control the duration and frequency of the beam spills, tape movements, and counting times. With these detector systems, the 8π spectrometer is able to provide comprehensive spectroscopic measurements that, at present, no other facility in the world can perform, and is used for studies in nuclear structure, nuclear astrophysics, and Standard Model tests. The TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS) is a next-generation γ-ray spectrometer that has been designed specifically for use at TRIUMF's new ISAC-II accelerated radioactive ion beam facility. The TIGRESS design is based on a 4π array consisting of 16 highly-segmented clover-type HPGe detectors with separately mounted bismuth germanate (BGO) Compton suppression shields that enable the array to be used in either a "maximum efficiency" or an "optimized peak-to-total" configuration. This design provides the versatility required to exploit the unique beams available at ISAC to pursue a broad research program with TIGRESS that will span the fields of nuclear structure, nuclear astrophysics, and fundamental symmetries. In conjunction with TIGRESS, a number of auxiliary detectors have been planned; CsI for charged-particle detection following fusion evaporation reactions, Si detectors for high-resolution charged-particle spectroscopy and Coulomb excitation, neutron detectors, PPAC's, Bragg detectors, etc.

The 8π and TIGRESS collaboration consists of 9 NSERC eligible researchers from Guelph, McMaster, Toronto, TRIUMF, Saint Mary's, and Simon Fraser. Five new hires have been made within the past 5 years, in the area of γ-ray spectroscopy applied to nuclear structure, nuclear astrophysics, and fundamental symmetries.

The proposed recoil mass spectrometer EMMA
Priority: Operating – High
New Capital – Very High

The ElectroMagnetic Mass Analyzer (EMMA) EMMA spectrometer will be a versatile recoil spectrometer that enables many nuclear structure and astrophysics experiments which cannot be done otherwise due to its high recoil detection efficiency and mass resolving power. The selection of a particular reaction with a recoil spectrometer is necessary when studying nuclei far from stability or with very weak intensity beams.

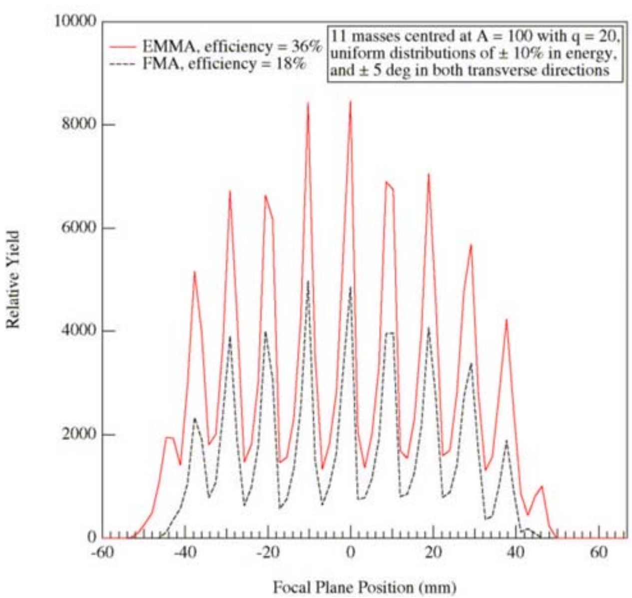

Figure 3-8: *Calculated mass spectra for EMMA and Argonne National Lab's FMA. Equal numbers of 11 nuclei with masses 95-105 and charge state 20 were propagated through the two spectrometers with identical beamspots and uniform angular and energy distributions (±10% in energy, ±5 deg in each transverse direction = 30 msr, 1 mm beamspot). The central energy is 1.8 MeV/nucleon and the central m/q = 5. These calculations reveal that EMMA is twice as efficient as the FMA and has superior mass resolving power.*

EMMA will be a next-generation recoil mass spectrometer to be constructed at TRIUMF ISAC-II, and will be the most advanced recoil spectrometer of the EME (electric dipole-magnetic dipole-electric dipole) type in the world, having unsurpassed solid angle (16 msr), energy acceptance (±20%) and large mass/charge acceptance (±4%). It has been specifically designed to be able to separate (d,p) single-nucleon transfer products from the beam. These types of reactions are extremely important in order to determine shell structure off stability. EMMA is also designed to have a large efficiency for detection of reaction products from fusion-evaporation reactions that probe nuclei at higher angular momentum than β decay or nucleon-transfer reactions. In many cases, the use of EMMA will allow for the unique identification of the nuclei produced in a reaction. Combined with proper focal plane detectors, products of reactions will have M and Z identification on an event-by-event basis. While it is anticipated that between 1/2 and 2/3 of all experiments using TIGRESS will require EMMA, there are also many that will use EMMA as a "stand-alone" device. As evidence for its future impact, we need only look to the coupling of the GAMMASPHERE γ-ray spectrometer (GS) with the Fragment Mass Analyzer (FMA) at Argonne National Laboratory is the U.S.. The physics program with GS+FMA has a breadth not possible otherwise, nor currently feasible elsewhere. The use of the FMA has not precluded the use of other auxiliary detectors, and has opened up areas not otherwise possible, with sensitivities not achievable at other facilities.

The range of physics that will be enabled with EMMA makes it a necessary instrument for the ISAC-II radioactive-beam facility. EMMA is a necessary investment for TRIUMF/ISAC-II, and it is assigned as the number one priority for new capital equipment funding in the next 5 years. A proposal for \$2.1M for the construction of EMMA was submitted to NSERC on Oct.1, 2005. Without a high-resolution mass spectrometer for ISAC-II, a large fraction of the scientific potential of the facility (and of TIGRESS), particularly for inverse (d,pγ) transfer reaction experiments that provide data for firm shell structure assignments will be lost. The EMMA facility is *the* funding priority of the nuclear physics community for new capital investment and must be funded within the status quo budget scenario.

The EMMA collaboration consists of 13 NSERC eligible researchers from Guelph, McMaster, TRIUMF, Saint Mary's, and Simon Fraser. Seven new hires will be using EMMA for a substantial part of their research once it comes on-line.

The DRAGON spectrometer
Priority: Operating – High

The DRAGON spectrometer at ISAC has been designed to measure weak resonances in (p,γ) reactions important for stellar burning and nucleosynthesis via the *rp* process. Heavy radioactive and stable ion beams with $A \leq 30$ are accelerated up 1.5 MeV/A. The heavy ion beam intercepts the windowless gas (hydrogen or helium) target and the reaction recoils are accepted at 0° into the recoil mass separator. Using magnetic and electrostatic elements in two main stages, the recoiling reaction products are separated from the beam, and are then detected at the focal plane. Beam suppression of the order of $\sim 10^{10}$ is achieved in this separator, and additional suppression is obtained when the recoil is observed in coincidence with the emitted prompt reaction γ ray (using a BGO array around the gas reaction chamber). In addition, time of flight and energy considerations allow further beam suppression, and factors up to 10^{15} have been observed. While designed for (p,γ) reactions, the physics program has expanded to include (α,γ) reactions. The collaboration currently consists of 11 NSERC eligible researchers from TRIUMF, McMaster, Simon Fraser, UNBC, and Toronto, including 3 recent hires.

The TUDA spectrometer
Priority: Operating – Medium
New Capital – Medium

The TRIUMF UK Detector Array (TUDA) detects charged particles emitted from reactions of radioactive beams with energies up to 1.5 MeV/A on stable targets. This facility is complementary to the DRAGON facility and its experimental program is necessary to complete the nuclear astrophysics studies at ISAC-I. DRAGON is designed for radiative capture studies whereas TUDA is used for exclusively charged particle reactions. For example TUDA will measure the cross section of the ^{18}Ne(α,p)^{21}Na reaction which is now suspected to be the primary breakout reaction from the CNO cycle to the rp-process.

The ISAC-I TUDA facility is an extremely flexible nuclear physics apparatus that can be modified (internally) to meet the needs of a variety of experiments. The current list of detectors that are available are two LEDA pancakes, made up of 8 Si sectors each with 16 strips, 300μm thick, another LEDA pancake with sectors that are 1mm thick, a CD detector, and 2×S2 detectors. The detectors can be positioned both upstream and downstream of the target up to 75 cm away. The chamber can accomodate both foil targets and gas cells. The rp-process breakout reaction uses a He gas cell and (^{3}He,p) reactions have been performed using a LN_2 cooled ^{3}He target. The chamber will be moved between ISAC-I and ISAC-II when the latter comes on-line. At ISAC-II experiments will be primarily transfer reactions like (^{3}He,p) studying nuclei of astrophysical interest. A collaboration with the TIGRESS group to develop a coordinated program is strongly encouraged.

The Canadian component of the TUDA collaboration consists of 7 NSERC eligible researchers from McMaster, Simon Fraser, UNBC and TRIUMF, with 2 recent hires in the past five years working on TUDA.

The reaction spectrometer HÉRACLES
Priority: Operating – Medium
New Capital – Medium

In order to determine the asymmetry parameter of the nuclear equation of state, reaction products are studied from a series of reactions varying the centre of mass energy and the neutron-to-proton asymmetry. Measurements must be performed that are sensitive to intermediate mass fragments produced in the collision, are able to measure fragment correlation functions, and can determine the emission chronology of the fragments. The detector HÉRACLES has been specially designed to allow these measurements, and has been used in successful campaigns at the Texas A&M accelerator facility. HÉRACLES is a highly segmented array of Si-CsI telescopes, CsI(Tl), plastic phoswich, and BaF_2 scintillation detectors that can discriminate between different particles ejected in the reaction. The collaboration consists of 3 NSERC eligible faculty from Laval.

3.2.4 Competition/complementarity to other International facilities and offshore experiments

There are now several radioactive beam facilities around the world pursuing similar physics to that outlined above. The most notable of these are the HRIBF and the NSCL in the United States, ISOLDE at CERN, RIKEN in Japan, GSI in Germany, GANIL in France, and TRIUMF-ISAC in Canada. Each facility has its particular niche. The NSCL, RIKEN, GSI, and GANIL have fast-fragmentation beams. While they can produce very exotic nuclear species that can either be used in intermediate-energy reaction studies or stopped and studied via β decay, the intensities of the available beams are typically much lower than ISOL-type facilities, like TRIUMF/ISAC. GANIL also boasts the SPIRAL ISOL facility, as do HRIBF, and ISOLDE. These facilities provide, in principle, direct competition to TRIUMF-ISAC. The HRIBF and ISOLDE facilities have been in operation the longest, and have well-established programs. HRIBF uses (typically) 40 MeV protons up to ~10 μA impinging on a uranium target, and specialize in the production of neutron-rich beams near the maxima in the mass yields of ^{238}U fission. ISOLDE uses typically 1 μA of 1 GeV protons on a variety of production targets. SPIRAL at GANIL uses fragmentation of high-energy, heavy beams on a thick C target, followed by ionization and acceleration. With a 500 MeV proton beam of potentially up to 100 μA intensity, ISAC has by far the highest driver beam power of the world's ISOL facilities and should thus produce superior secondary radioactive beam intensities; this is indeed the case for beam species that are produced and ionized in the same manner at, for example, ISAC and ISOLDE. However, ISOLDE's additional years of operation have allowed them to advance in the field of ion sources and targets such that they currently provide access to a wider variety of beams than ISAC. This situation should soon be remedied with the development of additional ion sources at ISAC and the actinide target. Once these developments are in place, ISAC will have world-leading intensities for almost all ISOL beam species, in some cases by orders of magnitude. The uniqueness of the spectrometers residing, or soon to be, at TRIUMF will allow them to take advantage of the high-intensity beams that no other facility can deliver. The DRAGON, 8π, TIGRESS, and TITAN spectrometers are world-leading facilities, and represent the cutting edge of instrumentation specially designed to maximize their physics impact. The EMMA recoil spectrometer will have 100% more angular acceptance than the current state of the art recoil spectrometer at Argonne while preserving better mass resolution and acceptance, and equivalent energy acceptance. This will be critical for experiments with low-intensity radioactive beams.

While the combination of radioactive beams and spectrometers make TRIUMF-ISAC a world-leading facility for performing nuclear science, the execution of the scientific program necessitates that some experiments be performed using unique facilities at foreign institutions. These collaborative experiments at other institutions not only allow us to perform leading-edge science, but also strengthen connections with the international community.

3.2.5 Long-range vision

The lion's share of the scientific programs for nuclear astrophysics and astrophysics will be carried out at TRIUMF-ISAC and ISAC-II over the next ~5 years. These have already been described in extensive detail. Looking further to the future, we consider several directions and developments that will ensure ISAC pre-eminence among the world's facilities for ISOL-based science and maintain Canada's role as a world leader in the field of radioactive-beam science.

TRIUMF-ISAC: The world's leading ISOL facility
Priority: Very High
As noted already, ISAC currently boasts the highest primary driver beam power among the world's ISOL facilities. The establishment of ISAC as *the* world leader in ISOL-based science, however, will require an intense program of ion-source and target development over the next several years and, in particular, the operation of an actinide production target to increase yields of neutron-rich isotopes and provide access to the trans-lead nuclei required by several fundamental symmetry tests. Significant personnel investments must be made in these areas if ISAC is to realize its full potential.

In order to efficiently develop new beam species, the TRIUMF 2005-2010 five-year plan called for the construction of a second 100 μA proton beamline to ISAC and a dedicated target and beam development facility. Within the context of the current TRIUMF budget profile, it does not appear that this project can proceed at the pace originally envisioned. Nonetheless, considering the crucial nature of beam development for the success of the ISAC facility, if new resources can be identified within the current 5-year plan (for example from CFI), initial phases of construction of the second proton beamline to ISAC and the dedicated beam development facility are considered the most important new initiative during this period. Looking toward the early part of the 2010-2015 five-year plan, we strongly endorse the concept that the second ISAC proton beamline should not be limited to 100 μA operation, but should explore entirely new ISOL beam-power domains associated with 200-300 μA operation. While initially devoted to target and ion source development in this new power regime, the infrastructure should be developed to couple the new production target area to ISAC experiments and parallel injector RFQ accelerator stages should be developed for the ISAC-I and ISAC-II accelerators. Looking toward the end of the current 10-year planning period we thus envision an ISAC facility comprising simultaneous operation of the current 100 μA beamline and the new high-power (200-300 μA) beamline with the capability to simultaneously deliver radioactive beams to any two of the low-energy area, the ISAC-I area, and the ISAC-II area – a truly world leading facility for ISOL-based science.

Considering the more distant future (beyond 2016), we strongly endorse the concept that R & D should begin within the current period (2006-2016) toward the design of a new high-power driver accelerator for TRIUMF to ensure Canada's continued position as a world-leader in ISOL science as well as exploring broader opportunities for accelerator-based science in Canada.

TIGRESS 16-detector completion
Priority: Medium
We have noted already that the TIGRESS design is based on a 4π array consisting of 16 highly-segmented clover-type HPGe detectors. A \$10.94M funding request over 6 years (FY03-08) to construct TIGRESS was submitted to the 2003 NSERC competition. The scientific proposal for TIGRESS received the highest recommendations from an international review committee and from GSC-19. Limitation of funds within the GSC-19 envelope, however, constrained the

amount awarded to \$8.06M over 6 years (FY03-FY08) with instructions to implement three-quarters of the array (12 of the 16 detector systems). In the scenario of a 20% cut in NSERC funding over the current 10-year planning period, the TIGRESS array could not be completed; otherwise, TIGRESS should be completed to its full complement of 16 detectors. This will require \$2.88M in additional capital investment and would naturally be accomplished through \$1.44M instalments in each of FY09 and FY10. In this context it is important to note that, unlike many situations, these last funding dollars will actually be the most cost effective and thus represent an obvious use of (and argument for) additional funding resources. While the final 4 detector modules for TIGRESS would only represent 25% of the capital cost of the array, they would provide a detection system that is 78% more efficient in γ–γ coincidence experiments than the currently funded 12-detector system. Every such experiment with TIGRESS at ISAC-II would thus require only roughly half of the beamtime, approximately doubling the scientific output. With development of new target and ion source technology at ISAC, the scientific impact of the facility will become limited almost entirely by beamtime availability. While the second ISAC proton beamline and simultaneous multi-user capability are the keys to addressing beam availability at ISAC, they must also be complemented by detection systems of the highest possible efficiency that can complete experiments with the shortest possible beamtime allocation. With the combined capital and personnel costs of the facility developments representing an investment of tens of millions of dollars, a 78% improvement in TIGRESS performance through completion of the 16-detector array for \$2.88M thus represents an extremely efficient use of funding resources.

8π spectrometer upgrade
Priority: High
The scientific programs at ISAC lie in either studying nuclei very far from stability, or probing nuclei with extreme sensitivity. In each case, the experimental limits are determined by a combination of beam intensity and detection efficiency and the significant investments in the ISAC facility to deliver the world's highest ISOL beam intensities must be complimented with detection systems of the highest possible efficiency. While the 8π spectrometer is currently a world-unique and world-leading facility for β decay studies with radioactive beams, the γ-ray group's vision foresees a significant capital investment to increase the efficiency of the 8π HPGe detectors and ensure that our facility retains its world pre-eminence. To this end, an array of 16 HPGe detectors, comprised of both clover detectors and planar detectors, is being considered. An array of this design could achieve high efficiency for both low-energy and high-energy γ rays simultaneously, and would increase the photopeak detection efficiency compared to the 8π spectrometer by more than an order of magnitude (a ~100 fold improvement in γ–γ coincidence efficiency). The capital cost will be approximately \$3M and a request to fund this upgrade will be made in ~2011, after the completion of TIGRESS, EMMA, and TITAN. The cost of construction would be spread over several (~ 3) years.

As an argument for the investment in the upgrade, some examples of the new reach of the science program, with such an increase in γ-ray detection efficiency, are given:

i) Examining nuclei at the extremes of existence. The 8π spectrometer can currently probe nuclei with beam intensities as low as 1–2 ion/s. With the upgrade of the γ-ray detection ability, spectroscopy could be performed with beam intensities as low as

0.01 ion/s. This will enable experiments on the crucial nuclei further from stability, providing a more complete picture of shell structure evolution and allow studies of nuclei closer to the *r*-process path.

ii) Examining nuclei at the extremes of structure. In order to differentiate between nuclear models, often it is the presence of very low-intensity, or non-existent, decay branches that provide the clearest signatures. The low intensity can result from the suppression due to phase-space factors, even if the nuclear matrix elements are enhanced. The non-existence results from the vanishing, or near vanishing, of matrix elements. The observation of weak decay branches allows the determination of the responsible mechanism and discriminating between very different mechanisms will differentiate between competing models of nuclear structure.

iii) Accurate branching ratios in super-allowed decays. As measurements proceed on higher-mass super-allowed β decays, the *Q*-value increases dramatically. This opens up the number of non-analogue levels that can be populated. These non-analogue levels receive a small, but important, population that must be accurately determined and an increased γ-ray detection efficiency, particularly for the high-energies typical of these decays (4–8 MeV), will be required for an accurate extraction of the super-allowed branching ratio. This is especially important for leading-edge measurements on A>62 Fermi decays, and also the $T_z=1 \rightarrow T_z=0$ decays.

iv) Improved spectroscopy on the Rn isotopes important for the radon electric dipole moment (EDM) measurement. An extremely high level density, even at low excitation energy, characterizes nuclei in the actinide region. In order to perform spectroscopy, high efficiency *and* high resolution must be obtained. A mixture of planar detectors, for high resolution and high efficiency for low-energy γ rays, and clover detectors, for high efficiency for higher-energy γ rays, combined with the ability to measure conversion electrons would enable spectroscopy to be performed with greater confidence in the level schemes and thus provide a more accurate determination of the degree of octupole deformation and parity-doublet splitting, and hence Schiff moment.

The option of using the TIGRESS detectors for β-decay experiments at ISAC-I is considered unsatisfactory for a number of reasons. The geometries of the TIGRESS detectors and their Compton shields have been designed for an array of 16 identical detectors and optimized for high-energy γ-ray detection efficiency. An upgraded 8π will consist of a mixture of clover and planar detectors with attention to low, as well as high, energy γ-ray detection efficiency and will have a completely different physical geometry. While the TIGRESS detectors can be removed from their support structure and transported from ISAC-II to ISAC-I, the large number of electrical contacts makes them more sensitive to potential damage during transit and such movement back and forth on a regular basis would be highly undesirable and could jeopardize the large capital investment in TIGRESS. More robust HPGe detectors without outer contact segmentation are both less expensive and better suited for experiments at ISAC-I. As TIGRESS will be the centerpiece experimental facility at ISAC-II, it is expected to be in high demand while the accelerator is operating. When TRIUMF develops the capability to deliver beams to both ISAC-I and ISAC-II simultaneously, large-scale γ-ray detector arrays optimized for the complementary research programs at each of these facilities will be essential. It is therefore deemed impractical for TIGRESS detectors to be used routinely for 8π experiments at ISAC-I, and a new ~\$3M HPGe system for ISAC-I will be proposed to improve the γ–γ detection efficiency of the current 8π Spectrometer by approximately a factor of 100 to make optimal use of the unique ISAC beams for far-from-stability β-decay studies.

The TACTIC detector
Priority: High
The TRIUMF Annular Chamber for Tracking Identification of Charged Particles (TACTIC) is a proposal for a cylindrical time projection chamber to be used as a detector for the measurement of low-energy charged particle reactions, covering nearly the full solid angle. The unique feature is that the central region contains a gaseous target which can also used as the detection gas in the field region. The chamber can register full traces of the reaction partners which include directions along with a full energy and an energy loss measurement. In addition, a time correlation with the primary beam is possible.

Due to this novel approach, such a system has many useful applications for nuclear reaction studies, relevant for nuclear astrophysics and nuclear structure. Moreover, this detector system could be employed in tandem with the TIGRESS array, EMMA, or TUDA. In order to maximize the efforts, collaboration with these groups would be particularly beneficial. Future upgrades are possible but depend on the initial performance. The experimental program still needs to be determined in detail., but the chamber will be used probe astrophysical reactions not accessible to the present TUDA chamber because of the low energies involved. Studies of the ^{8}Li(α,n)^{11}B reaction, a seed reaction for the *r*-process in type II supernovae, and ^{12}C+^{12}C fusion reaction, the detonator for type Ia supernovae, are planned.

Upgrade of TITAN
Priority: Medium
An obvious upgrade of the TITAN facility, alluded to earlier, is the installation of a cooler-Penning-ion trap, between EBIT and the Wien-filter, for beam quality enhancement. The sensitivity and precision of the mass measurements in the Penning trap are directly correlated to the observation, hence storage time of the highly charged ion in the trap. Both factors can be boosted by developing a cryo-cold Penning trap, where the complete trap electrode configuration is at LHe temperature. This would allow for two things: 1) the vacuum inside the trap would improve dramatically (this has been demonstrated with the Penning trap for anti-protons, where storage times of months have been achieved), and; 2) it would allow one to develop a non-destructive detection system, based on the fast Fourier transformation (FFT) of signals induced by the highly charged ions and picked up on the electrodes. This becomes possible only at low temperature, since the Johnson noise is sufficiently low and high quality tank circuits (Q values of more that 10000 are needed; only possible with superconducting coils) can be used. Such a system would allow the extension to very exotic isotopes, where the productions rates are as low as 1 ion/min. The extended storage time would guarantee excellent resolution, and provide an extension of the program of mass measurements in a significant manner. The projected cost of this upgrade is on the order of \$250k, and would be requested only in an increased funding scenario.

Development of a precision laser spectroscopy system
Priority: Medium

This is a new project at ISAC. Significant amounts of equipment have been obtained for no cost. When this is combined with equipment already available at TRIUMF, this will form a basis for a powerful and versatile system. A modest investment in peripherals to allow for the implementation of the equipment will result in an inexpensive system. The major expense over the coming years is expected to be for the personnel required to install and run the system.

The coupling of a laser spectroscopy system with the TITAN facility opens up new possibilities for extending measurements further towards the extremes of production by effectively decoupling the beam quality seen at the interaction region from that emitted from the ion source. The energy spread of all ion sources, whether they are surface, plasma or laser, will appear identical to the experiment, and an increase in the intensity in the bunches allows for a decrease in the background from laser scatter and photomultiplier dark currents.

The storage of ions in the buncher-cooler also opens up some interesting possibilities: 1) while being stored and accumulated it is possible to atomically manipulate the ions. This could potentially increase the signal strengths seen in the rare-earth region by at least an order of magnitude. 2) Another interesting possibility is to introduce a small quantity of a stable reference isotope of interest into the cooler-buncher along with the radioactive of interest, allowing for a direct measurement of the isotope shift can be performed. This technique will have the advantage of removing the uncertainty introduced by the knowledge of or fluctuations in the accelerating voltage. In this case fluorescence from the two isotopes will be separated in the interaction region by time of flight, the two isotopes having the same energy but differing in mass and therefore momenta.

Laboratory for Advanced Detector Development (LADD)
Priority: High

As is the case for all subatomic physics experiments, detector development is key to improving the sensitivity of the detection systems. The recently funded Laboratory for Advanced Detector Development (LADD) at TRIUMF through a grant from the Canadian Foundation for Innovation (CFI) provides an environment which will help Canadian groups conceive and develop new instruments. The second stage of LADD would provide facilities to produce state-of-the-art Si detectors and associated read out electronics as envisaged for the associated detectors proposed for TIGRESS or EMMA, as well as facilities for producing Gas Electron Multiplier foils as used in the TACTIC detector for example. Experiments with low intensity rare radioactive beams require advanced detectors for which LADD is particularly well suited.

3.3 What physics lies beyond the Standard Model?

3.3.1 Overview

The development of our understanding of the physics of our world is based primarily on the conservation laws and fundamental forces which are related to symmetries (global or local). It is hence very critical to test these symmetries to the best of our ability and in particular we must test the domain (energy scale) of their applicability. Our current best understanding of three of the four fundamental forces which govern our universe is embodied into the so-called Standard Model (SM) which has been constructed over the last forty years. It is based on the very general assumption of Lorentz invariance (independence of physics from space rotation and boost transformations) and assumes that the product of C(charge), P(parity) and T(time) symmetries is invariant. The current SM of particle physics assumes that CPT symmetry is true. It incorporates that P is observed to be maximally violated in weak interactions at the energy scales where we have been able to do tests and includes only V-A couplings. It also incorporates a small observed CP violation via a rotation of the weak and mass eigenstates through phases in the mixing matrix of the quarks (and possibly of the neutrinos) - hence T also is violated if CPT is to be a good symmetry.

Tests of theses assumptions have been and are still the focus of a large part of the physics research program in particle physics and in nuclear physics. Moreover, since the observed violations have been incorporated in an ad-hoc fashion, and since the model includes many arbitrary parameters, it is believed that the SM is only an effective approximation which has been extremely successful at the energy scale that we have been able to probe. It is also conjectured that a more encompassing theory should be developed which would be valid up to the Planck scale and would also incorporate quantum gravity (a force which is not yet included in the SM).

Many extensions to the standard model have been proposed which predict small but measurable deviations from SM predictions in terms of symmetry violations. While particle physics experiments at the energy frontier search for deviations that would be made more apparent with increased energy scales, nuclear physics has a complementary role to play in providing a special quantum laboratory where selection rules can be used to extract specific components of the interactions or enhance the violation effect in nuclei. The searches involve very high precision measurements of SM observables, or of phenomena forbidden or suppressed in the standard model. These "indirect" signatures of new physics can probe very large energy scales. For example a 4% measurement of the proton weak charge tests new physics at the 5 TeV scale and beyond, while rare decays of the muon can probe multi-TeV scales not accessible in accelerator-based experiments.

The main questions that are the focus of the field are:

i) The SM assumes that parity is maximally violated via a specific combination of vector and axial vector interactions. This assumption has only been tested to the 10% level and is thought to be valid at low energies compared to the weak scale (100

GeV). In a model-independent way one can write the basic interaction in terms of Lorentz invariant terms that transform like scalars, pseudo-scalars, vectors, axial vectors, and tensors. In its minimal form, the SM includes only the specific combination of V-A terms and hence exhibit maximal parity violation and CP and T invariance. The present set of experimental data cannot exclude the presence of a substantial amount of non V-A terms at the level of 10%. One goal of the nuclear physics symmetry program is to tighten these constraints in order to provide a set of discriminatory tests of possible extensions of the standard model.

ii) Is there a larger CP violation component beyond what is incorporated in the SM via the quark mixing matrix, which could explain the matter-antimatter asymmetry in our universe? Many extensions to the standard model include time violations (CP violation). To explain the neutral K decays observed 40 years ago, one introduced the concept of having the fermion weak eigenstates rotated away from the mass eigenstates. This is expressed today through the CKM matrix for the three generations of quarks and the PMNS matrix for the neutral leptons. The presence of the CP violation term introduced by the extra phase in the mixing matrix of the quarks has been confirmed by experiments in both the K-meson system and the B-meson systems. However, the level of CP violation produced by the so-called SM phase is too small to explain the present matter-antimatter asymmetry in our universe. The CP violating phase in the neutrino-mixing matrix has not yet been determined and its measurement is the main goal of the worldwide neutrino physics program. In any event, many extensions to the standard model induce large CP violation more readily than the standard model and the second focus of the low-energy symmetry tests is to search for evidence of such CP violation effects using the quantum numbers of nuclei to isolate specific contributions.

iii) Is the fundamental assumption of CPT invariance valid?

iv) Can we resolve the remaining pieces of the neutrino puzzle? We have a sense of neutrino mass splittings and mixings from the results of SNO for solar neutrinos, Kamiokande for atmospheric neutrinos, and the long-baseline neutrino oscillation experiments Kamland and K2K. However, we do not yet have a sense of the absolute mass scale for neutrinos.

New opportunities are available today to the nuclear physics community in Canada to help address these fundamental questions. They fall into two main categories of experimental developments (that build upon the recent evolution in laser technology and atomic physics techniques): 1) the development of efficient trapping techniques that have revolutionized the field of β-decay studies, precise mass determination, and correlations measurements, and 2) the availability of intense beams of exotic nuclear species from which one can exploit more discriminating selectivity. These two developments have opened the way for new sensitivity and much higher precision measurements. Canadian physicists are very fortunate indeed to be at the forefront in both of these areas with the Penning Trap, the TRINAT program and its extension to heavy francium atoms, the TITAN effort for highly charged ion traps and the ISAC facility for intense radioactive beams. This ISAC program is augmented by other precision measurements at

TRIUMF of purely leptonic decays and the pion decay branching ratio and by a selection of key complementary experiments at foreign facilities such as JLab, LANSCE, CERN, and J-PARC.

The following paragraphs outline the specific symmetry and standard model studies in which Canadian nuclear scientists are currently involved and provide an outlook on possible future initiatives in the field both at TRIUMF and abroad.

3.3.2 Experimental program

Precise determination of the quark mixing matrix element V_{ud}
Priority: High
The quark mixing-matrix parameterizes the rotation between the quark mass eigenstates and weak eigenstates. Its elements must be determined experimentally. The nuclear physics community is responsible for the determination of its largest element V_{ud}. This is obtained through precision measurements of super-allowed $0^+ \rightarrow 0^+$ β-decay transitions (Q value, branching ratio, and life time) and by assuming the validity of CVC. Strong collaboration with the nuclear theory community is required to evaluate the radiative and isospin dependant corrections to the experimental values. So far, this has been accomplished for nine such decays. CVC has been tested to the 3×10^{-4} level, as demonstrated by the equality of the corrected *ft* values. However, a test of the unitarity of the mixing matrix involving the sum of the square of the elements, as recommended by the Particle Data Group (PDG), in the first row is currently failing by more than a 2σ deviation. Detailed scrutiny of the existing measurements revealed some inconsistencies in the experimental determination of the Q values involved, which can only be resolved by more accurate mass measurements such as was done recently by the CPT group at Argonne National Lab (Phys. Rev. Lett. **95**, 102501 (2005)). Eliminating a set of suspect data, and with a detailed re-evaluation of the determination of V_{us}, the unitarity test may now be compatible with unity. While this is being resolved, the Canadian ISAC program has been developed to examine the theoretical corrections that must be applied to the experimental *ft* values, and also to increase the number of decays to include into the fit. In particular, odd-odd T_z=0 nuclei with A>62, where the isospin breaking corrections are large, are being measured to high precision, and some of the cases available in the 18<A<38 region will be revisited. With TITAN becoming available for precise mass measurements in 2006, the 8π spectrometer optimized for branching ratios and lifetime measurements, and a dedicated lifetime measurement tape system that has been tested to the required precision, all the components are in place to completely determine the *ft* values of the new cases as soon as the beams can be produced. The first case will be ^{74}Rb, for which all but an accurate mass measurement is missing. The next case will be ^{34}Ar, waiting for the new Febiad ion source which will be commissioned in Dec 2005. The following will be ^{62}Ga, for which beams are available. Within the next two years, ISAC could add these three cases to the fit with the required precision. This will provide a stringent test of the calculated corrections and allow for a determination of V_{ud} without eliminating suspect data. The resolution of the long-standing problem of the V_{ud} determination appears in view. Turning the argument around and assuming unitarity of the mixing matrix, one also can set limits on non *V-A* interactions in nuclear β-decay that are competitive with the other low-energy tests.

Searches for right handed currents in β–decay and muon-decay studies
Priority: High

Low-energy tests of the V-A structure of the electroweak interaction are conducted with elementary fermions, muons in the TWIST experiment (a Canada/Russia/USA collaboration) at TRIUMF and neutrons at the LANSCE cold neutron facility (Winnipeg), or using alkali neutral atoms (^{38m}K, ^{37}K, ^{80}Rb) in the TRINAT program (TRIUMF, Manitoba, Tel Aviv) at TRIUMF. The purely leptonic searches in polarized muon decay (TWIST) have an upper hand and provide constraints which are in the range of the direct searches at the hadron colliders (>700GeV). However, if one assumes that the right-handed mixing matrix has a very different structure or that the gauge coupling for right-handed interactions is much stronger than for the left-handed sector, then neutron and nuclear β-decay searches become much more favoured. The goal is to achieve comparable levels of constraints in all three programs.

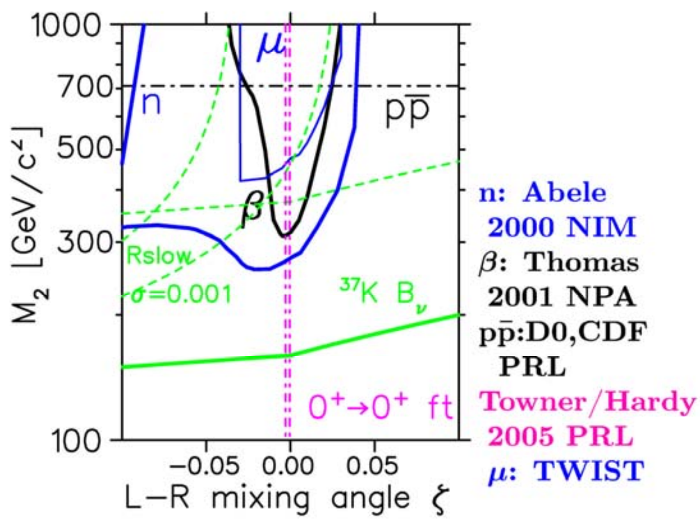

Figure 3-9 *In manifest left-right models, parity is restored by a heavy-mass W_R that couples to right-handed neutrinos. Many experiments have complementary exclusions of the W_R mass and its mixing angle with W_L. The present TRINAT 3% B_ν experiment in ^{37}K is shown in solid green. The goals of 0.1% in B_ν and R_{slow} are shown in dashed green.*

Searches for scalar interactions in beta, pion, and muon decays
Priority: High

The TRINAT program is also studying the β–ν angular correlation to place constraints on possible scalar bosons coupling to quarks of the first generation that, in some non-standard Higgs models, can be favoured. Nuclear β-decay provides the best limits on the first generation scalar interaction as obtained by the TRINAT group in the case of ^{38m}K decays (Phys. Rev. Lett. **94**, 142501 (2005)). The TWIST experiment also places constraints on scalar couplings in the leptonic sector, more specifically by looking at the η parameter that describes the low energy distribution of the decay positrons. This experiment is in its final stages and will conclude within the next few years. The $\pi \to e\nu$ branching ratio is very sensitive to any scalar couplings of new particles which avoid the helicity suppression of the dominant axial coupling. The 0.1% precision measurement of this ratio proposed at TRIUMF would, for example, probe mass scales for lepto-quarks in the 200-TeV region (see Kuno, Rev. Mod. Phys. **73** (2002)). Similar constraints can be placed by studying neutron β-decay and will form the focus of the Winnipeg/Manitoba group at the LANSCE facility and later at the SNS. Complementarity between $\pi \to e\nu$ and β-ν correlation constraints have been studied by Canadian theorists (B.A. Campbell, Nucl. Phys. **B709** (2005) 419).

Searches for tensor interactions in β-decay correlation studies and muon decay
Priority: High
There are indications of a small tensor force components in two radiative pion decay experiments that are not excluded by other constraints. It is important to confirm these observations in other systems. This part of the program is currently well underway at TWIST and TRINAT, where searches for such tensor components are carried out via measurements of spin correlations in beta and muon decay. For the TWIST experiment very large muon polarization is readily achieved but for nuclear beta-decay in traps new polarization techniques had to be developed. This is being achieved and one goal of the ^{37}K experiment in TRINAT is to search for second class currents (which are one form of tensor currents) with sensitivity greater than other beta-decay experiments, where the present best limits exist, complementary to those from existing or planned hadronic τ decays. Similar polarizations are foreseen for the neutron decay correlation measurements at LANSCE (the UCNA experiment) where, in principle, higher order corrections are known more precisely than in the nuclear case. However the two programs will produce very complementary information.

Electric dipole moment and other CP violation searches

Searches for CP violation beyond that incorporated in the standard model are being planned for the neutron, heavy deformed atoms, and neutrino sectors. Scientists from the Manitoba group are looking into the possibility of a neutron EDM experiment with ultra-cold neutrons at the SNS, the TIGRESS/TRINAT group has an approved program to search for EDM in the Rn isotopes, an LOI has been submitted for an EDM search with ultra-cold francium, a collaboration is being organized to join a search for T-Violation in charged K-decays at J-PARC, and the Canadian T2K group is part of the J-PARC neutrino program which will search for CP violation in the neutrino mixing matrix (this latter experiment is presented in the IPP program). This will form the backbone of the program in the medium-term extending well into the next decade.

The ^{223}Rn EDM experiment
Priority: High
An experiment has been approved at ISAC which will make use of the projected enhancement of the sensitivity to EDM in nuclei with octupole deformations. The most favourable case is that of 223Ra for which a factor 3000 enhancement is calculated. This enhancement requires a non-vanishing matrix element for the T-odd, P-odd operator r.I. This is realized in ^{223}Rn, where a parity mixed doublet with small energy difference is predicted. The establishment of octupole deformations and the determination of the parity-doublet energy differences requires detailed spectroscopy of the Rn isotopes to be performed with the 8π spectrometer.

The approved experiment at ISAC will depend on the availability of intense Radon beams that are planned at ISAC over the next few years. Considerable prototyping has already been done and a laser polarization scheme is developed. With TIGRESS modules becoming available in the next year, the experiment could be on the floor within two years and will take 100 data taking days to provide an order of magnitude improvement on the current best limit from the ^{199}Hg measurement.

Neutron EDM searches
Priority: High

The new efforts towards neutron EDM searches would rely on new ultra-cold sources of neutrons either at the SNS or possibly at TRIUMF. This latter option is not fully explored yet but would be based upon new idea for neutron cooling in supercritical He that is being tested at KEK. A workshop to evaluate these options should be held in the near future.

Search for T violation in kaon decays
Priority: Medium

A letter of intent has been submitted to J-PARC to propose an improved search for the transverse polarization of muons in both $K^+ \rightarrow \pi^0 \mu \nu$ and $K^+ \rightarrow \mu^+ \gamma \nu$ decays. This observable is very sensitive to new interactions since the Standard Model contribution is well-understood at the tree level and even beyond. A three order of magnitude window is available for exploration. The experiment would not start until the beginning of the next decade, subject to J-PARC's ability to produce more than one target station and one beamline. A Canadian collaboration is being formed.

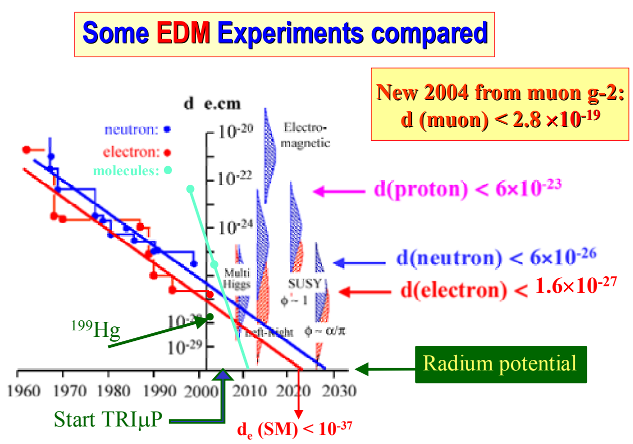

Figure 3-10: *Some EDM experiments compared with theoretical predictions from the standard model and various other models of particle physics. The current experimental limits are already placing restraints on the parameters of the various models.*

Search for CPT violation: The ALPHA project
Priority: High

Plans are under way by Canadian scientists to join the ALPHA project to search for CPT violation in hydrogen–antihydrogen atomic observables. Building upon the recent success in producing anti-hydrogen at the CERN AD facility, the first goal of the project is to develop trapping techniques for anti-hydrogen. Assuming that this is achieved in the proposed first phase of the project over the next three years, a physics program of symmetry tests will be developed for a second phase aimed at testing CPT invariance.

Precision measurements of the weak mixing angle

Canadian scientists are also involved in high-precision measurements of parity violation asymmetries in leptonic, hadronic, and atomic systems aimed at determining the fundamental structure of the weak interaction beyond the standard model via precise determination of the energy dependence (running) of the weak mixing angle, $\sin^2\theta_W$, at low energies (see Figure 3-11).

The Qweak experiment at JLab
Priority: High

At JLab, the Manitoba group is playing a major role in the Qweak experiment which is a precision measurement of the proton weak charge, $Q^p_{weak} = 1 - 4\sin^2\theta_W$, via parity-violating electron scattering on the proton at very low Q^2 and forward angles using longitudinally polarized electron beams. The measurement will provide the first high-precision measurement of the proton's weak charge with an accuracy of 4% on Q^p_{weak} or 0.3% on $\sin^2\theta_W$, with the aim of challenging the SM predictions and searching for new physics at the TeV scale. This measurement complements other completed weak charge measurements at low Q^2 including an atomic parity violation (APV) cesium measurement of $Q_{weak}(N,Z)$, the high energy neutrino-nucleus scattering NuTeV measurement, which observed a 2.5 σ deviation from the SM prediction, and the electron weak charge (Q^e_{weak}) measurement via parity-violating electron-electron (Möller) scattering (SLAC E158). Major equipment construction activities for Qweak are under way, installation will start in 2007-2008, and the measurements will be carried out in three stages between 2008 and 2012

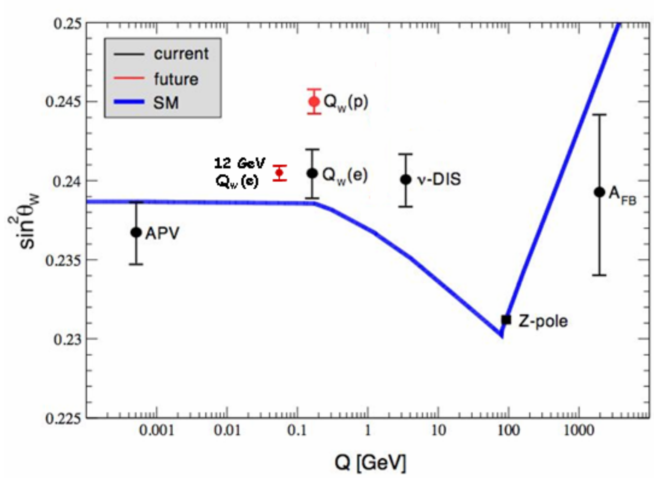

Figure 3-11: ***The running of $\sin^2\theta_W$ in the standard model. The black error bars show the current situation, while the red error bars (arbitrarily positioned on the vertical scale) refer to the anticipated precision of the Q_{weak} measurement and the possible future 12 GeV Möller scattering measurement at JLab.***

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12 GeV parity-violating Möller scattering at JLab
Priority: High

A future project also being planned by Manitoba group scientists and their international collaborators is a measurement of the parity-violating asymmetry in Möller scattering, to be carried out at JLab following the anticipated 12 GeV upgrade. The primary scientific motivation is to make the world's best measurement of $\sin^2\theta_W$ at low energies, by measuring the weak charge of the electron as in SLAC E158, but to a factor of five better precision (see Figure 3-11). The motivation for such a precise measurement would be strongly influenced by possible new discoveries at the LHC, in atomic physics, or in the Qweak experiment. This experiment would continue the search for new physics at the TeV scale, with possibilities to determine the couplings to electrons of new particles discovered at the LHC and to further narrow experimental bounds for the Higgs mass. A recent DOE review of the JLab upgrade cited this experiment as having ``discovery potential.'' The established expertise of the Canadian scientists involved and their long-term commitment to challenging high-precision experiments make this 12 GeV Möller experiment, which could potentially begin acquiring data as early as 2012, a natural extension to their current involvement at JLab in the G^0 and Qweak projects.

Atomic parity violation with ultra-cold francium
Priority: High

The running of $\sin^2\theta_W$ will also be investigated at ISAC via atomic parity violation (APV) measurements which constitute an important component of the new ultra-cold francium initiative led by a collaboration of scientists from Manitoba, TRIUMF, Stoney Brook, and Maryland. Such APV measurements have best been interpreted in the case of Cs (see Figure 3-11). The attractiveness of Fr is that its atomic theory can be understood at a level similar to that of Cs, but its APV effect is almost 20 times higher. These measurements will likely begin around 2009.

3.3.3 Long-term vision

The imminent start of the LHC is expected to have a major impact on the future of the field of particle physics and precision tests of the standard model. Any long term vision will have to react to discoveries along the way. The phase space for extensions of the standard model will hopefully be more restricted by the LHC results. A supersymmetric scenario, or a more complex scalar field sector may be identified. It will be very important to work out the implications of SUSY particles or of a more complex scalar sector in low energy processes and direct the program accordingly. To that end, theory support from particle physics phenomenology is needed.

Neutron and other EDM searches are projects of the highest priority because of their potential impact on many possible extensions of the standard model (see Figure 3-10). There is good theory support for such projects, so the issue for our community is basically an experimental one: Is there a possibility to create a competitive source of ultra-cold neutrons at TRIUMF and can we develop a francium EDM experiment with atomic fountains at ISAC? Similarly, muon rare decays can offer powerful constraints on various supersymmetry models, raising the issue of whether a super muon channel should be built at TRIUMF.

The key questions of the neutrino mass absolute scale and of the majorana or Dirac character of the neutrino will be the focus of several experiments at SNOLAB via neutrinoless double beta decay ($0\nu\beta\beta$) measurements. It will be important to carry out key nuclear structure experiments that will help validate the calculations of the $0\nu\beta\beta$ matrix elements. Again, the interaction here with nuclear theorists will be crucial.

3.4 Nuclear theory

3.4.1 Overview

It is clear from the preceding discussion that there is tremendous strength in the experimental nuclear physics program in Canada. In order that Canada can truly capitalize on this effort, it is important that this same strength be found in the theoretical nuclear physics program.

Canadian nuclear theorists have made tremendous contributions to our understanding of all aspects of subatomic physics. Work on super-allowed β-decay, semi-empirical mass formulae for r-process nucleosynthesis and the nuclear shell model have been major contributions of the more senior theorists to the traditional subject areas of nuclear physics. But there is also tremendous strength in the newer, forefront areas of nuclear theory. These include effective field theories for one, few, and many nucleon systems, lattice QCD, and relativistic heavy-ion theory and high-temperature QCD.

A significant problem looms for the nuclear theory community. Many of the outstanding nuclear theorists in Canada have retired, or are near retirement. While they will be active for many years to come, renewal over the next 10 years is critical to the continued efforts in the field. The level of renewal of nuclear theory in Canada over the past 10 years is a source of concern. There have been few new hires (Lewis, Regina, in lattice QCD; Barkanova, Acadia, electroweak physics in nuclear systems; Jeon, McGill (RIKEN), QCD at finite temperature), and only one coming (Schwenk, TRIUMF, effective field theory and many-body physics). It is critical that more hires be made in the period of this long-range planning exercise, and we will address means to stimulate that hiring later in this brief.

3.4.2 Current directions

There are significant contributions being made by Canadian theorists to our understanding of nuclear physics using conventional techniques, namely nucleon-nucleon potentials and the nuclear shell model. Towner (Queen's) and Hardy's work on superallowed β-decay has been instrumental in fixing the CKM matrix element V_{ud}, and is a shining example of how the understanding of the nuclear system impacts other areas of subatomic physics. This work is critical to the success of the Canadian experimental effort in superallowed β-decay, discussed earlier in this document.

The work of Rowe's group (Toronto) on the nuclear shell-model and collective phenomena integrates with the nuclear structure program at ISAC and provides an insight into critical phenomena in finite systems, complementary to the understanding gained in condensed matter physics for large systems.

Another significant contribution arises from the work of Pearson (Montréal) and collaborators on semi-empirical mass formulae for unstable nuclei. Experiments at radioactive beam facilities can extend our knowledge of many nuclear reactions and properties well away from the line of stability (thus important for nuclear astrophysics), but not all. Extrapolations are required to provide other subatomic physicists and astrophysicists with a complete set of data for reaction networks and kinematics (see, for example, Figure 3-12). Here, reliable many-body calculations and semi-empirical mass formulae are crucial, yet there are very few theorists worldwide contributing to this effort. Pearson is one of the leaders in this field.

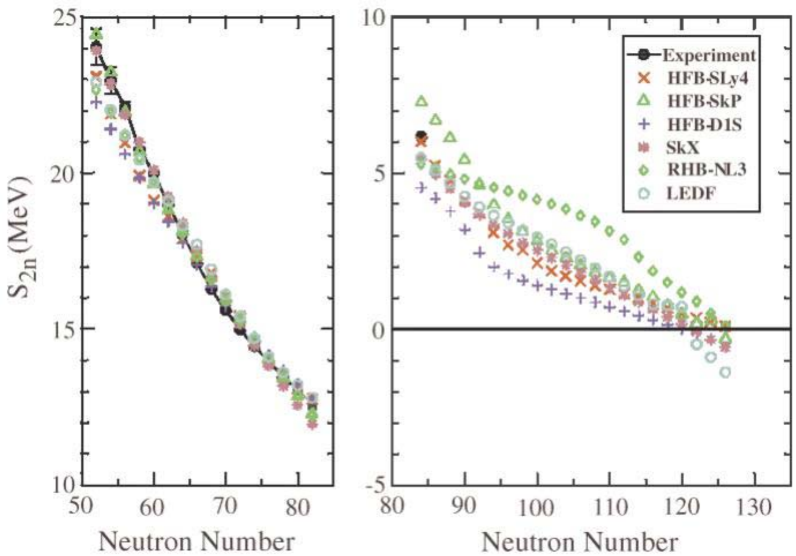

Figure 3-12: *Values of the two-neutron separation energy, S_{2n}, versus neutron number for the Sn isotopes. Where experimental data exist, up to N=84, the mass models reproduce the data reasonably well. However, uncertainties in the density functional result in a range of nearly 10 mass units of the limit of existence.*

Indeed, efforts in traditional nuclear physics, using well-developed phenomenological models, will continue to play a critical role for some years, and new methods are developed, tested, and refined.

There is also a significant effort in the physics of the quark-gluon plasma, headed by Gale (McGill), and the recent hires Moore and Jeon (Moore is a particle theorist with interests that overlap this area). These researchers have made outstanding contributions to the understanding of RHIC physics, and demonstrate well the impact a strong Canadian theory group can have on the international nuclear physics program.

There is a strong lattice QCD presence in Canada (Lewis, Regina; Trottier, SFU, Woloshyn, TRIUMF) with interests not only in lattice calculation of hadronic properties, but of interfacing the lattice with effective field theories such as chiral perturbation theory. The importance of this interface will be discussed later. Lattice QCD is being called upon more urgently by the nuclear physics community to help understand phenomena being observed at Jefferson Lab and elsewhere are we probe new regimes of hadronic structure. An example is the lattice calculation of the pion form-factor, shown Figure 3-13. There have also been significant instances of collaborative support between the Manitoba JLab group and the Canadian lattice community.

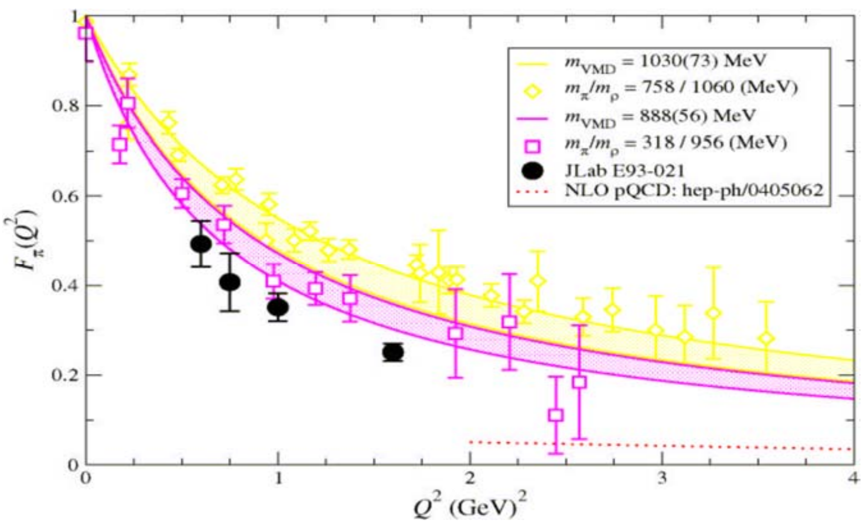

Figure 3-13: *Lattice calculation of the pion form factor, from Bonnet, Edwards, Fleming, Lewis, and Richards, Physical Review D 72, 054506 (2005). This is the only unquenched lattice QCD calculation of this observable. When the results are extrapolated to the physical pion mass, the results are consistent with the experimental results.*

The Canadian hadronic structure community has also benefited greatly from the contributions of Blunden (Manitoba) and collaborators, who have helped resolve a number of outstanding issues surrounding radiative corrections in that experiment. It was observed that the Rosenbluth separation results for the electromagnetic form-factors disagreed significantly with the recoil polarization results. This was shown to be due in part to the effects of electromagnetic radiative corrections, in particular two-photon exchange. A consistent treatment of radiative corrections is critical in these experiments in order to extract the small asymmetries, and Blunden *et al* made a significant contribution to this effort (see Figure 3-14).

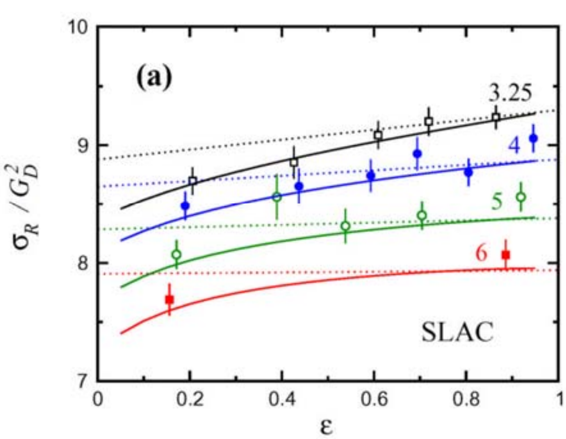

Figure 3-14: *Reduced electron-proton cross section σ_R versus virtual photon polarization ε (which depends on θ) for several values of momentum transfer Q^2 (in GeV^2). The dotted curves are Born cross-sections evaluated using a form factor G_E taken from polarization transfer data, whereas the solid curves include two-photon exchange contributions. A slight nonlinearity in ε is apparent in the solid curves.*

3.4.3 New directions

There are a number of new ideas in nuclear in nuclear physics that seek to connect our understanding of baryon-meson systems to QCD. These ideas are founded on the general principles of effective field theory. The most fundamental of these is chiral-perturbation theory (ChPT), namely the understanding of the meson octet as pseudogoldstone bosons coupled to baryon fields. This topic has been under study for many years, and Canadian nuclear theorists (e.g. Fearing, TRIUMF) have contributed significantly to our understanding of this topic. If is ChPT that also provides a link to lattice QCD, in that the effective field theory can be studied as a function of quark mass and used to extrapolate lattice calculations to physical quark masses (Lewis and group, Regina).

There are also a number of new approaches to studying few-nucleon systems using effective field theories (EFTs) and the renormalization group (RG). The long-range component of the nucleon-nucleon interaction is governed by one-pion exchange. Intermediate range effects are dominated by two-pion exchange, but even at those distance scales it is unclear whether this is a unique representation. At short distances, it is not clear that any sort of boson-exchange picture is relevant, or even resolvable in experiments. What is more important is having the correct coupling channels and a way of connecting unresolved short-distance physics to the long-distance physics governed by chiral symmetry. EFTs and the RG provide this connection. An interesting consequence is shown in Figure 3-15, where different nucleon-nucleon potentials are compared as a function of relative momentum. They all have quite different short-distance (high-momentum) structure. Yet, when that high-momentum physics is integrated out using RG methods, all the interactions converge to a single effective interaction. This effective interaction can then be applied, systematically in order to study the NN system in a consistent fashion. Further, as methods continue to develop connecting this approach to QCD (via extending the ideas of ChPT to few-nucleon systems), it becomes possible to consider studying two-nucleon operators in Lattice QCD and use the lattice to augment our understanding of nuclear interactions.

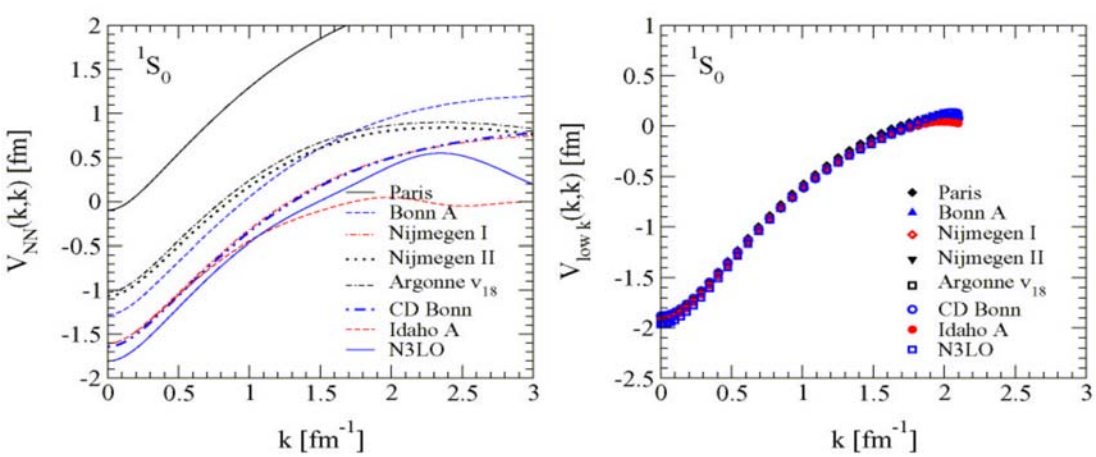

Figure 3-15: *Left figure: Different nucleon-nucleon interaction models $V_{NN}(k,k)$ versus incoming/outgoing momentum k. Right figure: The resulting low-momentum interactions $V_{low\,k}(k,k)$, derived by integrating out the high-momentum (p> 2.1 fm^{-1}) modes using the RG. The interactions are shown for the $^1S_0$ partial wave, but the same universal behaviour is found in all partial waves and for lower cutoffs.*

Finally, the ideas associated with EFTs and the RG are impacting the study of many-nucleon systems. Nuclear shell-model calculations require the diagonalization of a formally exact Hamiltonian in a viable Hilbert space. Formally, this space is infinite. The calculations are only tractable if the space is truncated. This is equivalent to introducing a cutoff into the theory, and the effects of that cutoff necessarily renormalize the interaction. This idea is not new, and has a long history in the form of the Bloch-Feshback-Horowitz projection operator formalism. The problem in this formalism is that the effective interaction becomes energy-dependent and the correct treatment of that dependence is exceedingly complicated.

In an RG-driven approach, the renormalized interactions are energy-independent, softer, and thus more manageable. This allows for a much more realistic treatment of the shell-model problem than ever-before realized. As ISAC and ISAC-II experimental programs probe further away from the line of stability, our intuition about nuclear structure weakens, and our ability to "guide" traditional shell-model calculations with that intuition fails. The new RG-driven shell-model approach will be vital in order to help guide, interpret, and extrapolate the results from ISAC and ISAC-II which are so important to nuclear astrophysics.

While this is an exciting new direction for nuclear physics, and is so important for the Canadian experimental program, there are few theorists working in this area. The new hire at TRIUMF, Schwenk, is a leader in this field and will play a crucial role in driving new efforts in this area and in collaborating with the experimental programs at TRIUMF. There are few other theorists in Canada working in this area (Butler, Saint Mary's) other than those already mentioned.

3.4.4 Long-range vision

It is clear that nuclear theory has an important role to play in collaboration with the experimental nuclear program, but also in the interpretation of nuclear phenomena in relation to the Standard Model. For this role to be met, renewal is critical over the next 10 years. There are a number of things that could be done to help nuclear theory in Canada. Experimental groups can lobby, actively, in their departments for theory hires to go to nuclear physics. This is difficult, but not impossible. TRIUMF could fund, as part of its next five-year plan, ISAC theory positions at the universities analogous to the JLab/RIKEN positions in the U.S. Even a modest number would have a tremendous impact. This by no means precludes augmenting theoretical efforts related to the strong Canadian experimental program at JLab (for example). The JLab/RIKEN positions went to strong nuclear theorists who strengthened the overall effort in nuclear theory (the labs would benefit indirectly from this – and they have). The same would hopefully be true for any equivalent positions created in Canada.

4. Facilities and Demographics

4.1 Facilities and infrastructure support for nuclear physics

4.1.1 Canadian facilities and infrastructure

The role of TRIUMF

As evident throughout this report, TRIUMF is a major resource for nearly all 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 radioactive beams in particular, TRIUMF is also the host facility to 400 external users representing 15 international countries. The continued development and delivery of high quality beams is clearly a very high priority item of the TRIUMF 5 Year Plan, and infrastructure improvements such as a second proton beamline to ISAC will be of great benefit to the nuclear structure and nuclear astrophysics 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. A noteworthy example is the support that the Manitoba group has received for the G^0 experiment at JLab. In this case, significant capital funds were received from U.S. collaborators and JLab, and the project was executed using the Manitoba group's manpower and expertise including vital infrastructure contributions from TRIUMF. These include detector and electronics construction at TRIUMF and associated beam tests in the TRIUMF meson hall. TRIUMF has received significant funds through CFI for the Laboratory for Advanced Detector Development. It provides an opportunity for developing new instruments tailored to the challenges of low intensity radioactive beam experiments most specifically combined gaseous target/ detectors (TACTIC) or Si based charged particle detectors and associated electronics. It also provides access to modern equipment for prototyping, calibrating, and testing new detectors as well as test beam facilities. TRIUMF's continued role as a base of national infrastructure support must be maintained with very high priority.

Given the small numbers of nuclear theorists in Canada, a "theory centre" which would host workshops, run visitor programs, etc. would be of tremendous help in allowing theorists to gather together to collaborate. The bias of this centre could be to support theorists engaged in understanding and driving the experimental program. The obvious location for this centre is TRIUMF, but it is not clear whether it should be part of the TRIUMF program or simply located at TRIUMF but funded through an MFA.

The emergence of SNOLab as a second Canadian experimental facility

The major CFI grant to build upon the successful SNO experiment and create an underground experimental facility of international significance is a great opportunity for Canadian physics. As discussed in the fundamental symmetries chapter of this report, experiments at SNOLab are expected to address a variety of urgent physics questions. These experiments typically involve international collaborations and are relatively small in nature. As such, they rely upon a central infrastructure in a manner similar to how most nuclear physics experiments rely upon a host user facility. The analogy between the role that the NRC has historically played in building up the TRIUMF infrastructure, and their possible role in support of SNOLab, has great merit and should be explored most seriously.

4.1.2 International facilities and infrastructure – USA

Jefferson Lab (CEBAF)

With the capability to deliver 6 GeV electron beams of unprecedented quality and stability, Jefferson Lab (JLab) is the world's pre-eminent facility in electronuclear physics. Over the past 15 years, the number of Canadian users of this lab has grown. They currently represent 7 Canadian institutions in 4 provinces, making it the largest concentration of Canadian nuclear physics effort outside of Canada. Over the longer term (2007-2012), JLab expects to upgrade its beam energy to 12 GeV, opening up a variety of new physics opportunities, and Canadian nuclear physicists have expressed considerable interest in continuing their efforts there. We also note the GlueX submission to the IPP, which is intended to shed further light upon the nature of confinement in QCD, as part of the JLab 12 GeV upgrade. Canadian contributions to the JLab program have had a very high impact to investment ratio, and should be supported with high priority.

Los Alamos (LANSCE) and Oak Ridge (SNS)

As discussed in Sections 3.1 and 3.3 of this report, two members of the Manitoba group (J. Martin, S. Page) are involved in fundamental neutron studies using the LANSCE facility at Los Alamos. The new Spallation Neutron Source (SNS) at Oak Ridge is expected to deliver dramatically higher neutron fluxes starting in 2008, and these researchers have proposed to relocate their efforts to this new facility.

Argonne (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 because of an entirely different production mechanism, where the radioactive species available at ATLAS are insensitive to chemistry. The isotopes are produced via in-flight in reactions as opposed to the target-diffusion technique applied at ISAC. Hence, for example, volatile species can be investigated which are traditionally excluded at on-line facilities.

The γ-ray spectroscopy group, involving physicists from Guelph, Saint Mary's, Simon Fraser, McMaster, and TRIUMF also perform experiments using the GAMMASPHERE spectrometer at the ATLAS facility to complement their radioactive-beams program.

HIGS

There has been a considerable investment of Canadian infrastructure from the former Saskatchewan Accelerator Laboratory to the High Intensity Gamma Source (HIGS) at Triangle Universities Nuclear Laboratory (TUNL) in North Carolina. This facility is currently being upgraded with a 1.2 GeV booster ring, which will increase both the energy and intensity of the available photon beams. A single Canadian principal investigator is involved in experiments at this facility.

4.1.3 International facilities and infrastructure – Europe

CERN

The ALPHA-Canada collaboration includes members from both the nuclear and particle physics communities, and draws upon Canadian expertise in atom trap physics and spectroscopy. They have leading scientific and technical impact within their collaboration.

Mainz (MAMI)

The Mainz Microtron (MAMI) in Germany has been recently upgraded to deliver 1.5 GeV electron beam. Along with a polarized photon beam and new frozen-spin target, this facility is expected to start a new series of experiments of relevance to QCD-physics starting in 2006. A single Canadian researcher (Hornidge) is involved in experiments at this facility.

4.1.4 International facilities and infrastructure – Japan

KEK and J-PARC

A Canadian group representing 4 institutions has been involved in KEK PS-E246, a study of T-reversal symmetry in the charged kaon sector. They were responsible for the SciFi target, which was developed by a joint collaboration of the University of Saskatchewan and TRIUMF, and graduated 1 Ph.D. student from this collaboration in 1999. Canadian researchers look forward to a second-generation experiment at the J-PARC facility, which is expected to open in 2009-10. This facility will deliver kaon beams of significantly higher flux and quality, offering an order of magnitude improvement in T-violation sensitivity. We also note that the T2K neutrino oscillation experiment will also utilize this facility.

4.1.5 High performance computing

There has been considerable discussion on a possible National High Performance Computing Center for Canada, especially in the context of the TRIUMF 5 Year Plan, and whether this would be of benefit to the Nuclear Physics community. Within nuclear physics, the most obvious users of high performance computing are those performing Lattice QCD simulations. These simulations are highly CPU-intensive, and typically require dedicated parallel processors, specifically configured to meet the needs of lattice calculations. As such, these computations can rarely be performed on a general-purpose system. The CFI has played a key role in providing Canadian researchers with the dedicated computing power necessary to make significant contributions to this field.

Should renewal in the Canadian nuclear theory lead to greater interest in ab-initio shell model calculations (related to ISAC experiments, for example), then these too will require access to large scale dedicated computing facilities.

4.1.6 MFA grants and nuclear physics

While nuclear physics collaborations and the use of facilities have both grown in recent years, the field has not taken full advantage of the funding programs available to support such activities. Major Facilities Access (MFA) grants are one example of this. The μSR user community at TRIUMF holds an MFA providing technical support on site at TRIUMF to support that experimental program. Clearly the Canadian ISAC user community could explore the merits of a similar support structure, as could the JLab users who access infrastructure support from TRIUMF.

4.1.7 The role of CFI in supporting university infrastructure

CFI has played a significant role in building up infrastructure at the university level. New Opportunities grants have supported the startup of new researchers. As mentioned earlier, it has also played a role in proving computing infrastructure in Canada. A critical problem encountered when considering CFI funding for experimental programs (and related infrastructure) is the one of matching funds. Many provincial matching fund programs have wound down, or grown more restrictive, making it difficult for applications related to fundamental research to find support. There is a need for the community and CFI to work with provincial governments to reverse this trend to help support experimental development at the universities.

4.2 The dynamics of nuclear physics research in Canada

Nuclear physics collaborations have grown significantly as efforts have moved to labs such as TRIUMF/ISAC and Jefferson Lab. Within these collaborations (which at Jlab, for example, may involve as many as 100 scientists) it is gratifying to observe that Canadians are assuming leadership roles both in defining the physics programs at these laboratories, and in carrying out to completion increasingly more challenging experiments. These leadership roles are connected directly to the quest to answer the fundamental questions mentioned in the introduction which represent the international priorities of nuclear physics.

Many examples of this leadership were seen in the physics overview sections of this report. At Jefferson Lab, Canadian researchers are spokespersons on high-priority experiments such as Qweak and the pion form factor experiment, or have acted as collaboration coordinators. At TRIUMF/ISAC, a number of new, young investigators from Canada are key proponents of new facilities for ISAC-II, such as TIGRESS and TITAN. Others are well-represented as spokespersons in the list of approved experiments. Canadian researchers are also playing leading roles in experiments being undertaken at HIGS, Mainz, Argonne (the Canadian Penning Trap), and Los Alamos (NPDGamma and UCNA). This breadth of involvement is very beneficial for the integrity and unity of the field, as many researchers are engaged in more than one subfield of nuclear physics. This, in turn, ensures the flow of ideas and insight from one subfield to another, strengthening the efforts in all.

It is also clear from this report that small universities and small groups can have a significant impact on new developments and new directions in nuclear physics. This is very powerful from the points of view of physics impact, productivity, and HQP training. The researchers (faculty, RAs and PDFs) and students (graduate and undergraduate) are involved in all stages of an experiment, from conception, through data acquisition, and analysis. Indeed, an individual researcher or small group can manage to support a number of ongoing parallel research activities so that HQP can be exposed to a broad range of scientific issues, and can see all the phases of experimental development during a relatively short timeframe. The relatively low cost of nuclear physics experiments means also that the impact/cost ratio is quite favourable, particularly for the small groups. Further, the HQP trained on these experiments have a very broad set of skills, which are applicable to experiments in all facets of subatomic physics (many of the proposed SNOLAB experiments, for example, rely on nuclear physics techniques as they probe questions of neutrino mass and dark matter composition).

It is particularly interesting to see the growth that is taking place in the collaborations surrounding the new facilities at TRIUMF-ISAC. In the TIGRESS/8π collaboration, for example, there has been dramatic growth in all HQP, as shown in Figure 4-1. This growth is representative of trends for the field, as will be discussed in the next section of this report. It indicates that the field is being seen to support cutting-edge research using state of the art technology, to be having a significant intellectual impact on science, and that it is contributing strongly to the training of bright young scientists who can contribute greatly both to nuclear physics and to other disciplines within subatomic physics and beyond.

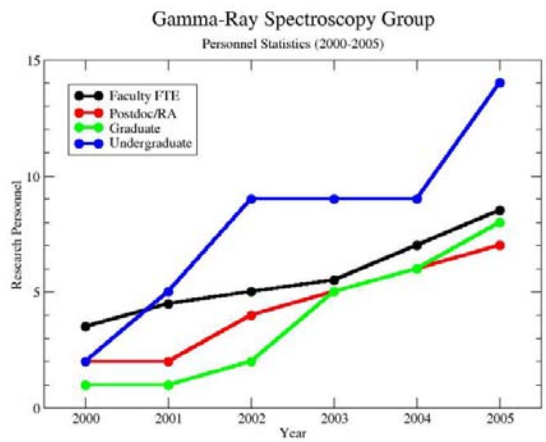

Figure 4-1: *Growth in the TIGRESS/8π gamma-ray spectroscopy group in the period 2000-2005. Note, in particular, the dramatic growth in the number of undergraduates involved in this research.*

4.3 Demographics of Nuclear Physics in Canada

The Nuclear Physics Brief Committee organized a survey to determine the strength and development of the field. The survey addressed the number and development of active faculty, grad and undergraduate students and post-doctoral fellows. The survey included all university physics departments, which have received grants from GSC19 in the last five years and TRIUMF. Active faculty is considered a faculty member that is engaged in an ongoing research program, either in a group or on its own, and can included emeritus professors. Undergraduate and graduate students considered are either NSERC or otherwise funded. The relevant research in nuclear physics is taken according to the definition used for international funding guidelines: nuclear structure, nuclear astrophysics, heavy ions, symmetry tests or reactions using low or intermediate-energy beams, non-perturbative QCD. All physics departments which have received funds from NSERC GSC 19 in the last five years and TRIUMF (32 departments in total) were included in the survey, which was sent to one contact person at each institution. This person was then responsible for retrieving the requested information from all relevant department members and university administration. We note here that the numbers presented represent lower limits on the actual statistics of each category. Not all departments responded, and in some cases it was not clear that the responses were comprehensive. Although the DNP membership numbers approximately 150 (primarily faculty), the responses indicated that there are about 80 faculty engaged in nuclear physics research. Some of this inconsistency may be due to the poorly-defined boundary between nuclear and particle physics, and the significant overlap between the DNP and IPP memberships.

Year	Undergraduate students	Graduate students	Post-doctoral fellows	New faculty hires
2001	42	46	28.5	4
2002	46	49	31	2.5
2003	51	53	32.5	6.5
2004	50	63	34	3
2005	56	73	42.5	3.5
Sum				19.5

Table 4-1: *Development of students, post doctoral fellows and new faculty members, who were or are involved in nuclear physics research for the years 2001 to 2005.*

The survey clearly verifies the trend that the field of Nuclear Physics is growing strongly. Over the course of the last 5 year period, from 2001 to 2005, 245 undergraduate students participated in nuclear physics research, growing 35%. Similar trends are observed for graduate students; where the number increased by 60%, demonstrating that nuclear physics is again a vibrant and attractive field of research for bright young students. The increase in student numbers is probably correlated to the new faculty hires that took place in this period. 19.5 new faculty were starting during the last 5 year plan (a half faculty indicates a split research activity between nuclear physics and a different discipline). The number of new hires balances the number of retirements which was 21 over the same period. Interestingly, however, most of the new hires took place at different institutions than where the retirements occurred.

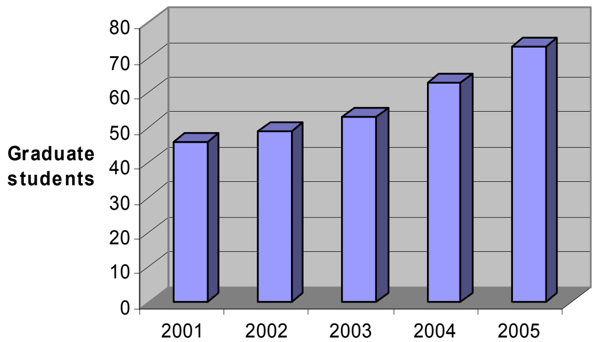

Figure 4-2: *Number of nuclear physics graduate students at Canadian physics departments and TRIUMF for the years 2001 to 2005.*

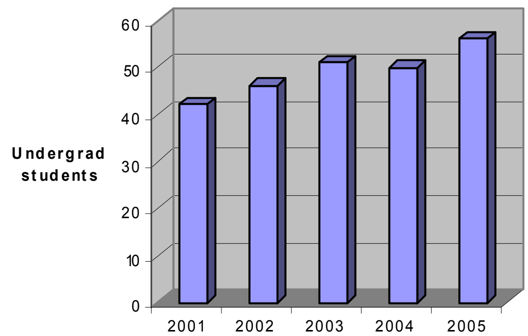

Figure 4-3: *Number of nuclear physics undergraduate students at Canadian physics departments and TRIUMF for the years 2001 to 2005.*

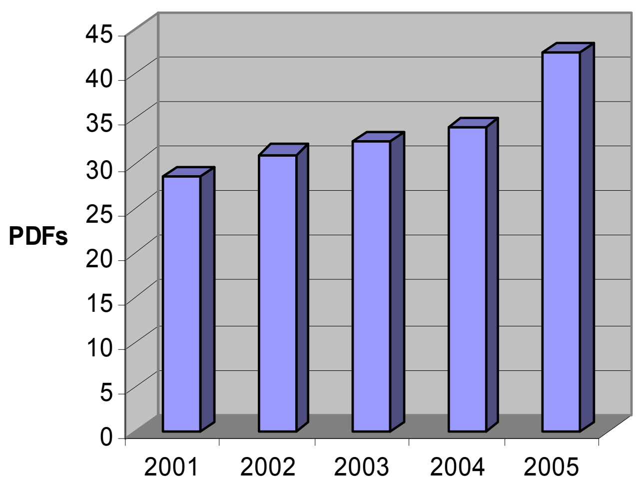

Figure 4-4: *Number of post doctoral fellows working in nuclear physics research for Canadian physics departments and at TRIUMF for the years 2001 to 2005.*

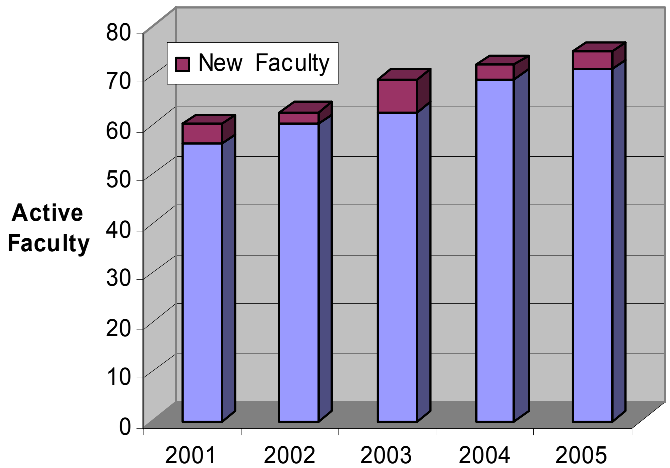

Figure 4-5: *Number of faculty members at Canadian physics departments and TRIUMF actively involved in nuclear physics for the years 2001 to 2005. Shown in red is the fraction of new faculty.*

The survey indicates a steady trend towards increased interest in nuclear physics at the physics departments and TRIUMF. The strongest increase, with 60% at the graduate student level, reflects the attractiveness of the field and the departments seem to be following suit with an increase in the hiring rate. Prognosis based on this trend and the scientific potential would point to continuous hiring of new faculty for at least 5 to7 years. While at this point the nuclear physics groups at departments have not yet reached the size of other comparable fields, or the levels that nuclear physics groups have traditionally enjoyed at some Canadian institutions, the observed trends are certainly encouraging and point toward a healthy revival of the field.

5. Canadian Nuclear Physics Funding Scenarios

5.1 Overview

Sections 4.2 and 4.3 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 in order to support that effort. In a scenario of NSERC funding to subatomic physics being increased by 100% over 10 years, this growth could be readily handled. Funding scenarios without growth (or worse reduced funding) would present a challenge to the field as it grows to its full potential.

Throughout this brief, the nuclear physics community has assigned priorities to its research endeavours. Separate priorities are given for operating vs. capital funding needs, where appropriate. These priorities are assigned based on how well the individual projects meet the physics goals outlined in the introduction, or how urgently capital funding is needed in order to permit experiments to meet those goals. In evaluating priorities we have excluded from this brief any program which would be ranked as low priority for the community. In fact, few low-priority items are even presented in the long-range planning process, simply because they have already been dealt with by the experimental review and evaluation committees at the major facilities. Thus, even with the most optimistic funding scenario presented here, we would expect to support only those projects ranked medium priority or higher.

Specifically, our rankings carry the following implications:

Very High: This is a new initiative which is vital to Canadian nuclear physics. It must proceed under all possible funding scenarios. In the -20% scenario, this would mean that we would cut deeply into other project funding in order to make these initiatives occur.

High: This is a priority item for funding. In the +100% scenario, high priority projects would be expected to increase significant new funds, while in the -20% scenario, funds to these projects would be preserved to the greatest extent possible.

Medium: This is a worthwhile project which should proceed in the status-quo and +100% funding scenarios. However, in the -20% scenario, funding to these projects would be jeopardized in order to preserve funds for higher priority projects.

Low: This is a project that is poorly-motivated or is of marginal scientific value. As mentioned, the brief committee has decided to exclude these projects from discussion in this report, as there is an ongoing process which screens these out even before the long-range planning exercise begins.

We have listed only two items as very high priority, with the remainder divided nearly equally between the high and medium priorities. These priorities were then used to generate funding tables for each of the scenarios outlined in the charge to the LRP process.

In the following sections, as well as describing the effects of the various funding scenarios we present funding tables that "snapshots" of needs. Under operating funds, we list the funds currently allocated or proposed for the various projects in nuclear physics, the anticipated funding level five years from now, and ten years from now. Under capital funding, we list the known/likely capital allocations in the next four years, and those that are anticipated to start five years from now (or later). As the capital needs are uncertain beyond that four year timeframe, we use an average of these four years to define a "typical" capital allocation to nuclear physics. This average is combined with the operating "snapshot" to define the total nuclear physics envelope in the current, five and ten-year snapshots.

5.2 +100% scenario

In this scenario, the GSC-19 funding envelope is expected to increase by +100% over a period of 10 years. This is an approximate 7% funding increase per year. This scenario allows many new nuclear physics initiatives to proceed in an optimal fashion. Further, it gives the discipline flexibility to explore new initiatives that would enhance our ability to tackle the physics questions outlined in the introduction, and driving the physics case presented in this brief.

Projects

TITAN: TITAN will have a high impact on nuclear structure, nuclear astrophysics, and fundamental symmetries. The TITAN initiative is nearing completion of its construction phase, with operation expected to begin in summer 2006. As TITAN is a new facility, it is expected to grow over the next few years, mainly in PDF's and graduate students associated with the program. The operation is recommended at a HIGH priority at a level of $320k currently, with $460k/yr in 5 yrs, and $550k/yr by 2015. The additional capital funding required for the 5th stage of TITAN, that would greatly increase the storage time of highly-charged ions in the trap, is projected at $250k to be appropriated in 2009.

CPT: CPT will have a high impact on nuclear structure, nuclear astrophysics, and fundamental symmetries. The CPT program is currently taking data, and complements the TITAN facility. The growth of the CPT is modest, from its current $200k to $224k in 5 years, to $250k in 10 years. No new major capital equipment has been indicated.

TRINAT: Under this context we include support for the Francium-symmetry tests to be re-located from Stony Brook Laboratory in the US to TRIUMF, and also projects by the Gwinner group at Manitoba. The TRINAT program has a high impact in the area of fundamental symmetries. The TRINAT program is expected to grow significantly, due to the inclusion of the Francium project, and the addition of Gwinner at Manitoba, from the current $280k/yr to $500k/yr in 2010. This level of support is expected to remain constant to 2015. No new major capital equipment has been indicated.

<u>*LASER:*</u> The LASER spectroscopy program lead by the Pearson group at TRIUMF is a new initiative currently at the level of \$0k. However, they have amassed a large equipment pool for the precision laser spectroscopy program at little or no cost to GSC19. The group projects that to perform the program, resources, mostly in manpower, on the order of \$200k/yr would be needed by 2010, and projected to remain flat thereafter. No additional capital equipment is foreseen.

<u>*8π/TIGRESS*</u>: The 8π/TIGRESS group, which in this context also includes the groups of Austin at St, Mary's, Garrett at Guelph,, Ressler at SFU, and a SAP project grant to study Fermi super-allowed β decays, has received a MIG for the construction of TIGRESS totalling \$8.06M over the period FY03-FY08, with amount of \$1.9M, \$1.8M, and \$1.1M in FY06, FY07, FY08 already committed. As the group turns from the construction phase to the operating phase of TIGRESS, in conjunction with the 8π spectrometer, increased operating funds must be made available. Since TIGRESS is the centerpiece facility of ISAC-II, and the group will have a high impact on nuclear structure, nuclear astrophysics, and fundamental symmetries, the 8π/TIGRESS operation receives a very high priority. The total group operating is projected to be \$1.0M in FY06, increasing to \$1.4M by FY10 and \$1.6M by FY15. New initiatives to be undertaken are the completion of the TIGRESS array from 12 to 16 detectors, at \$1.5M/yr in FY09 and FY10, and an upgrade of the 8π spectrometer at \$3M starting in FY11.

<u>*EMMA:*</u> EMMA, which in this context also includes the group grant of Davids at TRIUMF, will have a high impact on nuclear structure and nuclear astrophysics, and it is the number one priority for the community for new capital investment. The proposal submitted to GSC19 on Oct. 1, 2005 requested a funding profile of \$100k in FY06, \$1.0M in FY07, and \$1.0M in FY08. The operating costs associated with the facility are very modest, and projected to be only \$65k/yr by FY10. The FY06 number also includes the group grant of Davids at TRIUMF for nuclear astrophysics, currently at \$60k/yr, projected to grow to \$140k/yr by FY10 and remain constant thereafter.

<u>*TUDA:*</u> The TUDA facility impacts on nuclear astrophysics, and currently operates at \$74k/yr. The group requests growth to \$190k/yr in 5 years, associated mainly with an increase in PDF's. New capital initiatives by the group includes new LEDA detectors for experiments that are proposed (that would not have detectors provided by the UK collaborators), projected at a total of \$200k, and a total of \$450k for the TACTIC detector.

<u>*DRAGON:*</u> The DRAGON facility has a major impact on nuclear astrophysics, and has reached a stable situation with modest growth projected, from the current \$230k/yr to \$360k/yr by 2010, and \$450k/yr by 2015. No new capital initiatives are envisioned.

<u>*HERACLES:*</u> The HERACLES facility impacts on the nuclear reaction dynamics, and is in a stable situation with the projected operating costs level of \$225k/yr currently decreasing to \$200k/yr by 2015.

<u>*JLab:*</u> The G^0 and Qweak projects at JLab are expected to be completed over the next 5 years, and in all scenarios this effort is expected to largely transfer to the 12 GeV Möller experiment at JLab. Based on the size and expertise of the Manitoba group, we expect significant contributions

to the 12 GeV Möller experiment to be made. We estimate this could include approximately $1 million in capital construction money in ~2010, for items such as dedicated spectrometer magnets and detectors for this experiment. We also expect operating costs for these efforts to increase from $420k to $550 k in five years.

The JLab/MAMI/HIGS hadron structure program will proceed with maximum scientific output. New funds would be largely allocated to PDF support, which would augment the experimental effort, and allow Canadian investigators to have full impact in their respective collaborations for the analysis and interpretation of their results. In the latter half of this plan, we expect most of this effort to take place at the upgraded 12 GeV JLab.

ALPHA: The Canadian investigators have leading roles in the antihydrogen symmetry test at CERN, and should be supported with high priority. In addition to the $185k in equipment funds requested for 2006, we project approximately $500k in additional capital funds to be required in 2008-10, for items such as a pulsed pump laser and a new superconducting magnet.

Pienu Experiment at TRIUMF: This experiment is still in the formative stage, but its physics aims are clearly of high priority, as it has the potential to place useful limits to scalar extensions of the standard model. Because a variety of options are still under consideration, estimates for new funds for this experiment are highly uncertain. We project this experiment to require funds in the 2007-2012 timeframe, and with completion prior to the end of this 10 year plan.

New initiatives in R&D phase:

In the last 5 years of this 10-year +100% funding scenario, up to $4 million/year could be allocated by year 10 to new initiatives which are not yet defined. Because the demographics of the nuclear physics community have changed significantly during the last 5 years, and they are expected to continue to evolve over the next 10 years, we expect these ill-defined new initiatives to be largely-led by potential new hires to nuclear physics. Here, we list some possible new initiatives which may arise.

Additional Initiatives at the JLab 12 GeV upgrade: The number of Canadians actively pursuing experimental research at Jefferson Lab has increased consistently over the past 5 and 10 year time periods. Most recently, these have been new hires at universities which did not have pre-existing nuclear physics programs. If funding to nuclear physics grows at a healthy pace over the next 10 years, it is quite likely that new Canadian-led initiatives at JLab will be proposed over the coming decade, requiring a mix of new operating and capital funds.

Fundamental Neutron Physics: This long-range plan already foresees Canadian participation in fundamental neutron research at LANSCE and later SNS. Experiments such as the neutron EDM at SNS hold much promise, and Canadian contributions to these measurements could be further strengthened if new-hires have interest in this area. The community might also consider developing an ultra-cold neutron source in Canada, possibly at TRIUMF.

High Intensity Source for Rare Muon Decay Studies: Another possibility would be to launch a new generation of rare muon decay experiments, perhaps to confirm signatures of supersymmetry observed at LHC. Such searches would require infrastructure to create high intensity muon beams, either at TRIUMF, or elsewhere.

TRIUMF Upgrade: The early success of the ISAC program has generated demands for beamtime from the ISAC scientific community that far exceed the capability of the lone ISAC production line. TRIUMF had asked funding for developing a second proton beam extraction in its five year plan. This was not funded, but it is crucial that the proton economics at TRIUMF be improved by continuing the program of upgrades to the cyclotron intensity and providing another ISAC production line. This would also be necessary for considering some of the long term prospects mentioned for the fundamental symmetry test program (UCN, Muons sources). The proposed Major Science Investment initiative of the federal government would be essential to allow this initiative to proceed.

We also emphasise that the TRIUMF accelerator group is a unique resource for Canada which should keep abreast of the many research and development efforts in high power accelerators worldwide and provide long term options for increasing the beam capacity of TRIUMF.

Future SNOLab Experiments: The nuclear physics community lends considerable support to the SNOLab experimental program. Some of projects to be launched in the near future (e.g. Majorana) are first generation experiments, with the clear intention to considerably upgrade them as funds become available.

25 GeV Electron-Light Ion Collider: The Brookhaven and Jefferson Laboratories in the USA have competing long-term proposals for an electron-light ion collider. The motivation is to study the Generalized Parton Distribution description of the nucleon in unprecedented detail, and there have been a number of user workshops on this proposed facility in the past few years.

+100% scenario	Priority	Operating funds/year			Priority	Capital				
In $K/year		Now	In Year 5	In Year 10		06	07	08	09	10 onwards
ISAC										
TITAN	high	$320	$460	$550	medium				$250	
CPT	high	$200	$224	$250						
TRINAT/UMan/SB	high	$280	$500	$500						
-laser spectroscopy	medium		$200	$200						
8pi/TIGRESS	very high	$1,000	$1,400	$1,600	committed	$1,900	$1,800	$1,100		
complete TIGRESS					medium				$1,500	$1,500
8pi upgrade					high					$3,000
EMMA	high	$60	$200	$220	very high	$100	$1,000	$1,000		
TUDA	medium	$74	$190	$190	medium	$40	$40	$40	$40	$40
TACTIC	high	$65	$126	$126	high	$110	$63			
TACTIC upgrade					medium					$100
DRAGON	high	$230	$360	$450						
HERACLES	medium	$170	$160	$160	medium	$55	$50	$40	onward	
Jlab/Mainz/HIGS										
G0	high	$210								
Qweak	high	$210	$400		high	$150	$150			
12 GeV Moller	high		$150	$550	high				$500	$500
Hadronic	high	$175	$250	$360						
HIGS	medium	$57	$75	$98						
Other										
n beta decay	high	$10	$80							
NPDgamma	medium	$25	$80							
pienu	high		$200		high	$200				
K-decay	medium		$400	$400	medium		$100	onward		
Alpha	high	$325	$430	$430	high	$185		$200	$200	$100
Totals		**$3,411**	**$5,885**	**$6,084**		**$2,740**	**$3,203**	**$2,380**	**$2,490**	**$5,240**
New Initiatives			**$1,500**	**$4,000**			**Capital Average**		**$2,703**	
Capital Average+Operating +New Initiatives		**$6,114**	**$10,088**	**$12,787**						
Status Quo	**$6,091**									
Change in expenditure		**N/A**	**66%**	**110%**						

5.3 Status-quo scenario

In this scenario, Canadians will seek answers to a wide variety of nuclear physics questions, as discussed in the physics chapters of this report. In order to maintain the scientific capabilities of these experimental pursuits, the capital budget for long-term projects which are already proposed are fully preserved, but no funds are identified for future initiatives which are still in formation. The nuclear physics operating budget would also likely decline with time, as some existing projects are completed but not replaced with new ones. Any new initiatives which are still in formation would have to be delayed until after 2016.

In this Status Quo funding scenario, the operating budgets for the existing programs remain at the FY06 level without any increase, except for those that are currently (or soon to be) under a MIG, or those that are just beginning and for which no funds have been requested for FY06. These exceptions include EMMA, for which operating funds begin in FY09, the laser spectroscopy program for which capital equipment has already been received outside of the GSC19 envelope, the work with n-decay and $np \rightarrow d\gamma$ that are just beginning and must have increased support level, and the pienu and K-decay programs. These latter two programs might more appropriately fall under the purview of Particle Physics, but certainly represent the overlap of Nuclear and Particle Physics. The operating funds for the new ISAC programs are modest at $65k (EMMA) and $200k (Laser) annually. The neutron experiments, pienu and K-decay represent a more significant investment in operating funds, totalling $760k/yr in 5 years, but have a potentially large scientific payoff and should be supported. We see that the operating funds grow from the current $3.3M to $4.3M in 5 years (a 30% increase), but this mirrors the growth in faculty and scientific staff (~35% increase) in the past 5 years; new hires whose programs must be supported out of the envelope.

The surge in the number of FTE's working in the field of Nuclear Physics, especially those associated with ISAC-based science, has put an additional demand on the experimental facilities. In order to maximize the science output of the flagship of TRIUMF, ISAC and ISAC-II, we still call for major ISAC capital investments for TITAN ($250k), TIGRESS ($1.5M) and TUDA ($200k) that represent a constant capital equipment investment. These investments result, however, in an overall 17% increase in FY09 for Nuclear Physics out of the GSC19 envelope. The scientific arguments for these capital equipment investments have been outlined in previous Sections. We have not attempted to "fine-tune" these capital expenditures into FY10 and beyond, which could be done to lower the impact in FY09. Instead, using the TIGRESS completion as the example, we argue that the increase in the scientific output (completion of TIGRESS would result in a near doubling of the number of experiments performed with ISAC-II) is very appropriate use of GSC19 funds. Given the increase in new faculty in Nuclear Physics, with the subsequent increase in PDF's, graduate students, undergraduate students, etc., many of whom perform their research at ISAC and ISAC-II, the demand on the experimental facilities will continue to grow, and the most efficient use of the available beam time must be made.

Status quo	Priority	Operating funds/year			Priority	Capital				
In $K/year		Now	In Year 5	In Year 10		06	07	08	09	10 onwards
ISAC										
TITAN	high	$320	$320	$320	medium				$250	
CPT	high	$200	$200	$200						
TRINAT/UMan/SB	high	$280	$280	$280						
-laser spectroscopy	medium		$200	$200						
8pi/TIGRESS	very high	$1,000	$1,000	$1,000	committed	$1,900	$1,800	$1,100		
complete TIGRESS					medium				$1,500	$1,500
8pi upgrade					high					$3,000
EMMA	high	$60	$120	$120	very high	$100	$1,000	$1,000		
TUDA	medium	$74	$74	$74	medium	$40	$40	$40	$40	$40
TACTIC	high	$65	$126	$126	high	$110	$63			
TACTIC upgrade					medium					$100
DRAGON	high	$230	$230	$230						
HERACLES	medium	$170	$160	$160	medium	$55	$50	$40	onward	
Jlab/Mainz/HIGS										
G0	high	$210								
Qweak	high	$210	$270		high	$150	$150			
12 GeV Moller	high		$150	$420	high				$500	$500
Hadronic	high	$175	$175	$175						
HIGS	medium	$57	$57	$57						
Other										
n beta decay	high	$10	$80							
NPDgamma	medium	$25	$80							
pienu	high		$200		high	$200				
K-decay	medium		$400	$400	medium		$100	onward		
Alpha	high	$325	$325	$325	high	$185		$200	$200	$100
Totals		**$3,411**	**$4,447**	**$4,087**		**$2,740**	**$3,203**	**$2,380**	**$2,490**	**$5,240**
Capital Average+Operating		**$6,114**	**$7,150**	**$6,790**			**Capital Average**		**$2,703**	
Status Quo	**$6,091**									
Change in expenditure		**0%**	**17%**	**11%**						

5.4 -20% scenario

This scenario requires that we make a number of very hard decisions and we are forced to eliminate a number of otherwise very worthwhile projects. In this case, the committee tried to preserve the greatest portion of the Canadian nuclear physics scientific impact in a very difficult situation, particularly in light of the discussion surrounding the status-quo scenario in the previous section. Thus, capital expenditures are projected to take the greatest brunt of the budget cuts (25% cut in capital, while operating is cut by only 12%).

It is inevitable that, in this funding scenario, a number of principal investigators would see their research funding ramped to zero over the next 5 years, resulting in an expected contraction of the field by 6.5 FTEs. The number of HQPs would similarly be very adversely affected. This would have a catastrophic impact on the growth the field has seen in recent years (Section 4.3), particularly in graduate and undergraduate students. It is clear that if not subsequently reversed, such cuts would have a very negative long term impact upon the field. There would also be a serious impact to areas of great importance to society as a whole, such as nuclear medicine, radiation protection, nuclear safety and nuclear power generation.

The –20% scenario would have a major impact on the ISAC physics programs. In this scenario, all medium priority items are cut, resulting in the loss of the laser spectroscopy program, the HERACLES program, and the TUDA program, and also the TIGRESS 16-detector completion. We have opted for this rather than across the board cuts in order to maximize the physics from the high-priority facilities which must be supported to the full extent. The consequence of this choice is that Canada will fail to realize the full potential of the investment it has made in the ISAC and ISAC-II facilities over the last 10-year period.

The JLab experimental program is of high priority and is protected to the greatest extent possible, but the program at HIGS is at risk of elimination in this scenario. Of the fundamental neutron studies in the USA, we make the hard decision to eliminate one of them (NPDGamma) in favour of preserving Canadian impact in the other (neutron beta decay).

The T-odd kaon decay experiment at J-PARC would also likely not proceed in this scenario.

To summarize, a 20% cut in funding to subatomic physics would seriously harm the nuclear physics program in Canada. The successes we have had in new facility investment, in faculty renewal, in HQP training and recruitment would be lost. Further, the loss of HQP training in nuclear physics would impact many other areas of society. Nuclear physicists play a role in nuclear medicine, radiation protection, nuclear safety, and nuclear power generation, to name a few areas that would be hurt by the reduction.

-20% scenario	Priority	Operating funds/year			Priority	Capital				
In $K/year		Now	In Year 5	In Year 10		06	07	08	09	10 onwards
ISAC										
TITAN	high	$320	$320	$320						
CPT	high	$200	$200	$200						
TRINAT/UMan/SB	high	$280	$280	$280						
8pi/TIGRESS	very high	$1,000	$1,000	$1,000	committed	$1,900	$1,800	$1,100		
8pi upgrade					high					$3,000
EMMA	high	$60	$120	$120	very high	$100	$1,000	$1,000		
TUDA	medium	$74	$0	$0						
TACTIC	high	$65	$126	$126	high	$110	$63			
DRAGON	high	$230	$230	$230						
HERACLES	medium	$170	$0	$0						
Jlab/Mainz/HIGS										
G0	high	$210								
Qweak	high	$210	$270		high	$150	$150			
12 GeV Moller	high		$150	$420	high				$500	$500
Hadronic	high	$175	$175	$175						
HIGS	medium	$57	$0	$0						
Other										
n beta decay	high	$10	$50							
NPDgamma	medium	$25	$0							
pienu	high		$200		high	$200				
Alpha	high	$325	$325	$325	high	$185		$200	$200	$100
Totals		**$3,411**	**$3,446**	**$3,196**		**$2,645**	**$3,013**	**$2,300**	**$700**	**$3,700**
Capital Average+Operating		**$5,576**	**$5,611**	**$5,361**			**Capital Average**		**$2,165**	
Status Quo	**$6,091**									
Change in expenditure		**N/A**	**-8%**	**-12%**						

5.5 Other initiatives:

Nuclear Theory Centre: Canadian nuclear theorists have made tremendous contributions to our understanding of all aspects of subatomic physics. Some of those contributions were highlighted in Section 3.4, but many others exist. We must ensure that advances in nuclear theory and experiment continue to progress in concert. Many of the outstanding nuclear theorists in Canada have retired or are near retirement. We need to sustain a vibrant theory community which includes young minds who can build upon theoretical advances of recent years, particularly some of the ideas introduced in this past decade. These efforts would be greatly facilitated by the establishment of a national Nuclear Theory Centre. Using the JLab and BNL/RIKEN theory centres as models, one of the activities of the envisioned centre could be to advance the interests of nuclear theory nationwide and act as a catalyst for the continued health of the field.

The role of the centre would be to facilitate collaboration, both between theorists and between theorists and experimentalists. Funding allocated to the centre would be directed towards visitor programs, conferences and workshops. The intent is not to provide funding for a concentration of personnel, but to provide collaborative resources for the personnel already in place at institutions across Canada.

Institute of Nuclear Physics (INP): Nuclear physicists have discussed for many years the desirability of an umbrella organization to advance their interests. The primary purpose of the Institute of Particle Physics is to provide umbrella-financing for the complement of IPP Research Scientists. There is *no* intention or desire on the part of nuclear physicists to ask for similar research scientist funding, so the scope of any possible INP would be significantly different than the existing IPP. Rather, we see the need for a formalized organization which could represent the voice of the nuclear physics community at the GSC-19 Large Projects Day, for example. In some aspects (such as this SAP long range planning process), the DNP is already a voice for the nuclear physics community in a manner that the PPD does not attempt. However, as a division of the CAP, the DNP is barred from receiving NSERC funds which could be used to organize annual workshops of interest to the Canadian nuclear physics community, or other initiatives, which other organizations such as the TRIUMF and SAL User's Groups have previously received NSERC funds for. Since the DNP is at present the only Canadian nuclear physics body with representation from all of the Canadian nuclear physics groups, we suggest that this institute could be formed as an arms-length body of the DNP. The institute would require a formal charter and executive, and if the nuclear physics community is in favour, it could be brought forward as an item for discussion at the next DNP business meeting in St. Catherines. The funding demand from the GSC-19 envelope would be very modest (<$50k/yr).