2011–16

The Subatomic Universe: Canada in the Age of Discovery

Report of the Natural Sciences and Engineering Research Council of Canada (NSERC) Long-Range Planning Committee

Cover: Theorists working on new ideas at the Perimeter Institute in Waterloo, Ontario

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Reaping the Opportunities for Canada

A. The Quest to Understand and Innovate

This decade may well see a revolution in our understanding of the nature of matter and its interactions, as we seek answers to questions about our universe such as:

- Do we understand the origin of mass?
- What is the nature of the dark matter controlling the structure of the universe?
- Might neutrinos hold the key to understanding the dominance of matter over antimatter in our universe?
- Can we understand and explain the nature and origin of the atomic elements?

Subatomic physicists across Canada are working on projects that seek to answer these and related questions.

Canada is positioned for discovery and innovation in subatomic physics through careful planning and public investment. Over the past 10 to 15 years, the Canadian subatomic physics community has placed particular focus on a small number of flagship projects both domestically and internationally. It has balanced this with a robust theory program that supports these projects and incubates new ideas and innovation. But it has also been judicious in ensuring the flexibility required to react to new opportunities for discovery and development.

Canadian society has benefited substantially from this research, socially and economically, through the training of highly qualified personnel and the innovation that it fosters. However, maintaining this position of leadership in the future is a challenge. There are new opportunities presenting themselves to Canada and the Canadian subatomic physics community. Seizing them will ensure that Canada enhances its role in subatomic physics over the coming decades, and that the nation can continue to reap the benefits. Here, the NSERC Subatomic Physics Long-Range Planning Committee presents its conclusions and recommendations for fulfilling this vision.

B. Working Together for Discovery

Canadian subatomic physics is in an enviable position worldwide. As opportunities ripen and breakthroughs occur, agility and flexibility will be required to maintain Canadian relevance and readiness and to ensure the returns on scientific investments.

The 2006-11 plan has served us well and, as we look forward to 2011-16, we are well-positioned for Canada to:

- reap the scientific reward from the investments it has made in A Toroidal LHC ApparatuS (ATLAS), Tokai to Kamioka (T2K) and the SNOLAB and Isotope Seperator and ACcelerator (ISAC) experimental programs;
- maintain a strong theoretical program in place both for leadership on the fundamental questions and for collaboration with the associated experimental priorities;
- be strategic and engage in selected discovery-potential experiments;
- engage in research and development (R&D) for the next-generation flagship experiments; and
- ensure continued access to, and support for, the domestic and international laboratories that are key to meeting the scientific priorities of the Canadian subatomic physics program.

There are new opportunities on the horizon that would build on current Canadian successes and further strengthen our leadership. The Canadian subatomic physics community will face key decisions in the 2011-2016 period that will determine the physics priorities beyond 2016.

- What project at the energy frontier will become our next priority when the definitive results from ATLAS are published?
- How will Canada exploit the physics potential of TRIUMF's Advanced Rare IsotopE Laboratory (ARIEL) to maintain our leadership in radioactive beam physics?
- Could an upgrade to T2K provide insight into the dominance of matter over antimatter in our universe?
- Will the Enriched Xenon Observatory (EXO) adopt Canadian technology and look to be situated at SNOLAB?
- Will the subatomic physics community have the resources at its disposal to perform the R&D required for any/all of these opportunities?

Control room of the ISAC-II facility at TRIUMF

C. Recommendations

Providing Value for Investment

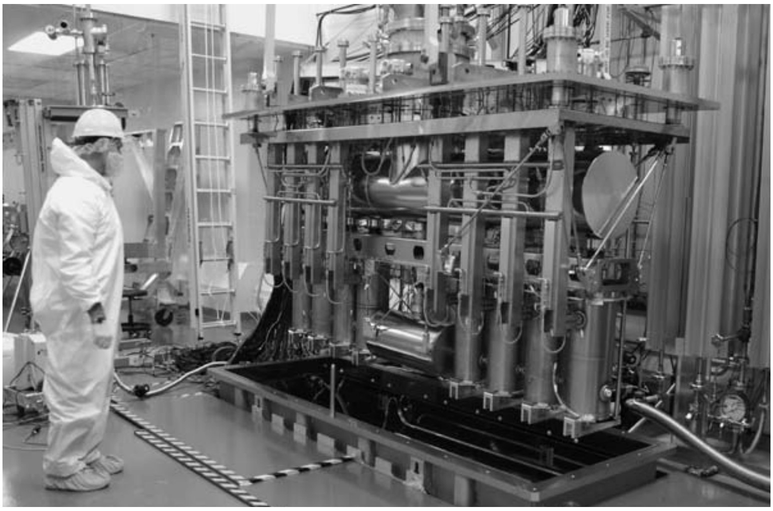
- The subatomic physics envelope has served the Canadian program very well, and we urge NSERC to maintain its support for the envelope model.
- The level of NSERC funding to subatomic physics should be increased by $3.5 million per year over the course of this plan, to allow Canadian researchers to fruitfully exploit the public investments to date.
- The priorities for the subatomic physics envelope must remain the support of research and discovery activities.

Working Together to Deliver the Scientific Reward

- Maintain the ongoing investment in subatomic physics research support and infrastructure from all agencies.
- The community and the various funding bodies—NSERC, Canada Foundation for Innovation (CFI), etc.—should work together to ensure the most effective and strategic use of research support and infrastructure provided for subatomic physics research.
- The community encourages the Government of Canada to pursue the possibility of Associate Membership at the Centre European pour la Recherche Nucleaire (CERN) laboratory.

Supporting Canadian Innovation

- Ensure ongoing support for the training of highly qualified personnel (HQP) and their contributions to entrepreneurship and innovation in the Canadian economy.
- Provide opportunities for Canadian industry to bid on contracts related to the leading-edge developments in manufacturing, service, and information technology taking place at CERN and other global laboratories.



Cryomodule for the TRIUMF ISAC-II accelerator

2

The Fundamental Questions

1. The Nature of the Composition of the World Around Us

The scientific mission of subatomic physics is to identify the elementary constituents of matter and their physical properties, identify the fundamental forces through which they interact, and identify how these ingredients combine to produce the organization we see around us in nature. Unusually, we stand on the threshold of a complete rethinking of our answer to these questions, which will force us to discard the Standard Model—the theory that embodies the 40-year-old consensus as to what these basic constituents and forces are—and replace it with a new and even better description.

Four centuries of study reveal that nature comes to us in an enormous hierarchy of scales, ranging from elementary particles of the smallest sizes up to the observable universe as a whole on the largest distances. What ultimately makes the study of nature possible at all is the remarkable fact that we don't need to understand all of these scales at once; an understanding of the flow of traffic doesn't require detailed knowledge about the engines that propel the vehicles involved, so an understanding of atoms does not depend on a detailed knowledge of nuclei. The properties of nature at any one scale are largely independent of detailed physics at smaller scales and it is this independence that allows physics to progress.

Despite this general observation, some of these details do turn out to be important for our explanation of the properties of larger systems. The properties of car engines do constrain the average speeds that characterize the flow of traffic. Similarly, some chemical and thermal properties of matter depend on the size of atoms; atomic sizes depend on the properties—mass and couplings—of their constituent electrons and nuclei, and so on. For this reason, the properties of matter on scales smaller than the size of atoms play a fundamental role in science; they underpin many of the explanations of why larger things behave the way they do. Physics at these smallest scales matters even for extremely large objects, all the way up to cosmological scales.

Subatomic physics represents the cutting edge of our knowledge of physics on the smallest scales to which we have access. The context for the rest of this document starts with a summary of what has been the paradigm up until now, together with the reasons why this is believed now to require improvement.

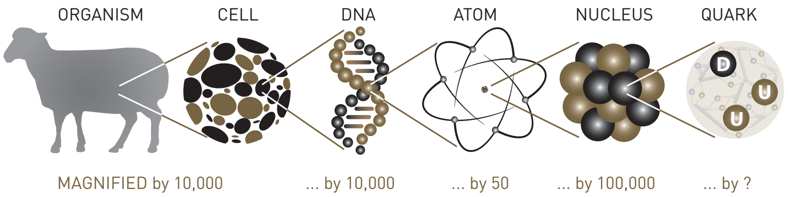


Figure. 1: Examining matter on ever smaller scales. As we zoom-in on detail, we see smaller structures emerge. Quarks seem point-like, no matter how closely we look.

a. What are the constituents of matter?

The 20th century saw enormous progress in identifying the fundamental constituents of matter. In the early 1900s these were thought to consist of several dozen types of atoms, together with some oddities like the then-recently- discovered electron and products of radioactive decay. The discovery of quantum mechanics and the nucleus then allowed the many properties of atoms to be inferred from those of neutrons, protons and electrons. The recognition that nuclei are themselves built from smaller things eventually led to a much more economical list of fundamental objects—protons, neutrons and electrons.

New particles—muons, pions, neutrinos and a host of other new particles—continued to be discovered. They were initially found through studies of radioactivity and the cosmic rays that continuously bombard the Earth from space, but then by colliding particles in man-made accelerator facilities. This temporarily led to a much more complicated picture, whose underlying simplicity did not emerge until the 1960s, when many of the particles known by that point were themselves found to be made up of still smaller constituents. What then emerged as elementary particles remain so now: six species (or flavours) of "quarks" (up, down, strange, charm, bottom and top) and six species (or flavours) of "leptons" (electron, muon, tau and three species of neutrinos).

The resulting list of particles is strangely redundant. Essentially all of everyday matter is made up only of electrons and up and down quarks (the last two of which make up the proton and neutron) which, together with a neutrino, make up what is called the "first generation" of elementary particles.

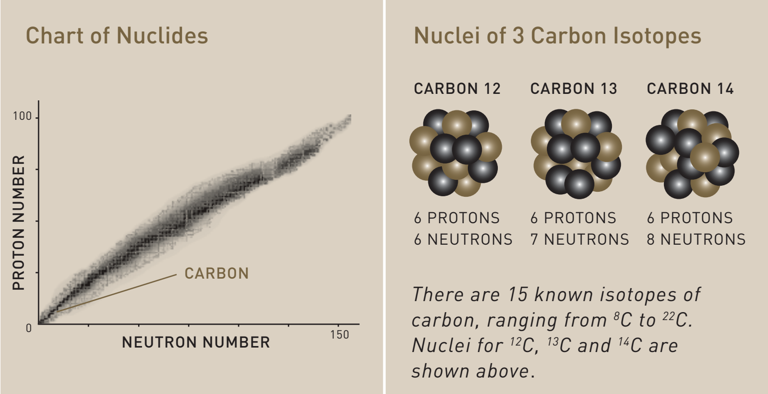


Figure 2: The atomic elements that make up matter around us are actually rich in structure. Elements, defined by their proton or "atomic" number, have many different isotopes—same proton number, but different numbers of neutrons. Even a simple element like carbon has 15 known isotopes.

Remarkably, nature seems to come to us with two more "generations" of particles, whose properties directly copy this first generation (i.e., the charm and top quarks resemble the up quark; the strange and bottom quarks resemble the down quark; the muon and tau are copies of the electron; and so on). The reasons for this seemingly redundant particle content, and the origins of their complicated pattern of masses, remain unclear; a puzzle known as the "flavour problem."

b. How do the constituents interact?

Progress has also been made identifying the forces through which constituent particles interact. Four interactions are now recognized as fundamental, only two of which—gravity and electromagnetism—had been identified in the 19th century. The other two—the strong and weak forces—emerged later as the interactions responsible for binding quarks into protons and neutrons, and these into nuclei, and for some of their radioactive decays. In the modern description, each of these forces is associated with a field, whose quanta—gravitons, photons, gluons and W and Z bosons—can also be produced in reactions much like any other elementary particles.

The Standard Model

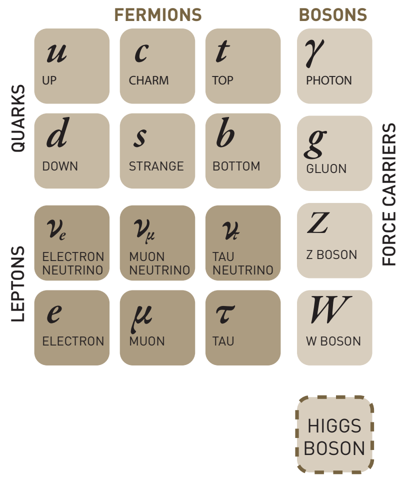
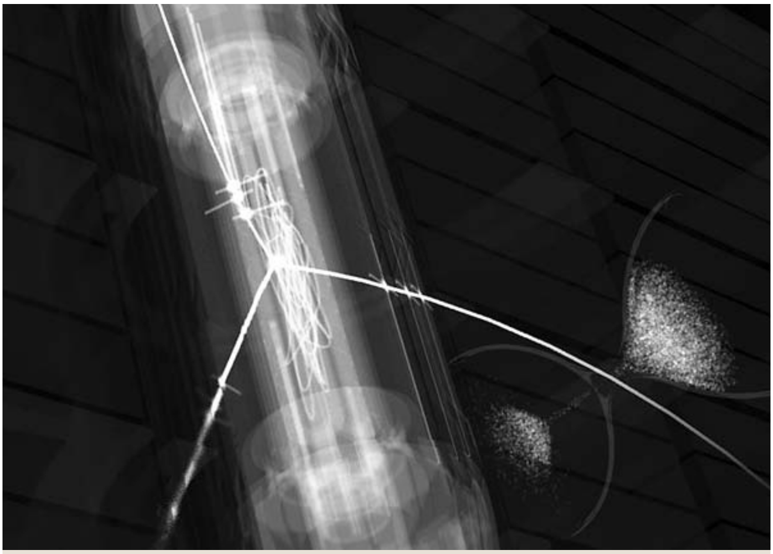


Figure 3: The particles of the Standard Model of particle physics. The Higgs boson has yet to be observed.

The 1970s saw a great synthesis of these constituents and interactions into a very successful theory—the Standard Model—which survives (only slightly battered) in our own day as the best theoretical benchmark we have. The Standard Model describes in detail how the fundamental quarks and leptons interact through three of the four forces—the weak, strong and electromagnetic interactions. It also postulates one hitherto undiscovered particle—the Higgs boson—whose presence (or the presence of something similar) is required by the theory's mathematical consistency. The Standard Model has nothing to say about the fourth force—gravity—which remains beyond the pale. Although well-described over astrophysical distances by Einstein's Theory of General Relativity, well-established theories do a poor job of describing gravity over very short distances where quantum effects become important.

One of the Standard Model's great successes is the way it naturally explains the many patterns that had been inferred from observation in numerous experiments over the years. In particular, it accounts for and explains several exact and approximate conservation laws that appear to work very well in practice. Among these are the approximate conservation of "parity"—invariance under reflection through a mirror—by three of the four interactions; the approximate conservation of CP (parity together with the interchange of particles with "antiparticles" (see the pull-out box on antimatter); the exact conservation of CPT symmetry—charge conjugation symmetry (C) and parity (P), together with time reversal symmetry (T)—which is fundamental to quantum field theory and is the basis of the Standard Model and many of its hypothesized extensions; the conservation of baryon number, B—which counts the difference between the number of quarks and anti-quarks, inferred from the absence of proton decay; and the separate conservation of "electron number" L_e , "muon number" L_μ and "tau number" L_τ.

Because the explanation of these "fundamental symmetries" is such an important part of the Standard Model's success, a great deal of experimental effort is spent checking that they are really present in nature in precisely the way the Standard Model predicts. Such tests are often called the "precision frontier," since they involve precise searches for rare reactions that are predicted by the Standard Model never (or only rarely) to occur. The hope is to find examples where the Standard Model gets it wrong, since this would provide clues to building the new theory that would be its replacement.



Antimatter

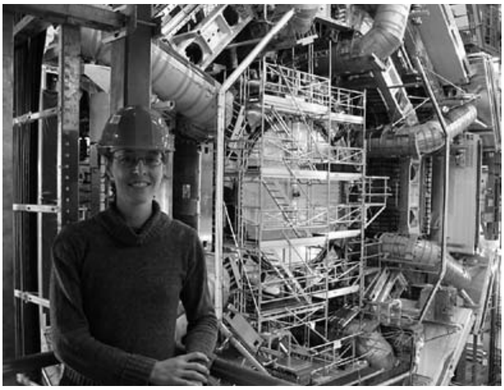
It is an experimental fact of nature that for each elementary particle discovered there is always another, called its antiparticle, with exactly the same mass and exactly opposite charge (the electric charge and any other conserved charge carried by the particle, like baryon number). The only time antiparticles are not found is when a particle does not carry any conserved charges at all, in which case it can be regarded as being its own antiparticle. Antiparticles always interact with the same strength as the corresponding particles. In the modern understanding, this remarkable duplication of particle species is no accident, being required by the consistency of two pillars of modern physics: quantum mechanics and relativity. It is a triumph of our modern understanding that antiparticles, required by theoretical consistency, are actually found in nature with exactly the right properties.

c. How are they organized?

The discoveries leading to the Standard Model provide a precise snapshot of the constituents of matter and their interactions down to distance scales that are just now beginning to be surpassed. Although this represents a major achievement, it is only the first step towards understanding the world around us, which involves interacting collections of many particles.

Experience shows that systems with many particles often aggregate into complicated states that exhibit a broad diversity and richness of properties. Typically, the particles that interact the strongest organize themselves into bound states on the smallest scales. Quarks and gluons (which interact via the strong force) typically bind to nuclear matter, taking any of a myriad of forms—nuclei, protons or neutrons, a charged gas of quarks and gluons (a "quark-gluon" plasma)—depending on the pressures and temperatures involved. Larger systems built from these, such as atoms and molecules, are usually bound through the next-strongest interaction—electromagnetism. The weakest long-range force—gravity—is the main player in determining the structure of the largest of objects, such as planets, stars and galaxies.

While the Standard Model provides a precise description of the interactions between the fundamental particles, understanding these complex structures is a much more difficult problem. In particular, the complexity of atomic nuclei and the rich variety of their properties and excitations, which in turn determine the number and stability of the chemical elements, are governed by the strong interactions, but a detailed understanding of the properties of nuclei from the Standard Model has been a challenge for decades. It is difficult to connect the properties of nuclear forces to the underlying strong interactions between quarks and gluons and equally difficult to understand



A Canadian physicist beside the ATLAS detector.

the properties of complex nuclei in terms of the basic nuclear forces. Remarkably however, with recent computational, theoretical and experimental advances, we are now making tremendous progress on both of these goals. Calculations can now make direct connections between the strong interactions and the properties of protons and neutrons, and the nature and reactions of more complex nuclei are beginning to be understood from their basic proton and neutron ingredients. Indeed, through observations of rare isotopes that are too unstable to be found naturally on Earth, but that can be artificially produced and studied in the laboratory, we are now on the threshold of a unified understanding of the connectivity between the diversity of nuclear structures—from atomic nuclei to neutron stars.

d. Where did it all come from?

A deep understanding of the world around us does not stop with describing its structure; it also asks where it came from. This is particularly pressing given the compelling evidence that the entire universe was once so hot and small that it consisted only of a soup of elementary particles. Given this simple beginning, how has all of the intricate structure of the present-day world arisen?

This question comes at several levels, depending on how far back into the early universe one chooses to go. Our world today is built up of some 300 different kinds of stable atomic nuclei that formed, together with electrons, the atoms and molecules that built up all the materials around us. In the very early universe, protons and neutrons did not exist—instead the universe consisted of a hot quark-gluon plasma. Approximately a microsecond after the Big Bang, as this quark-gluon plasma cooled, the dynamics of the strong interaction required that quarks and gluons become confined in neutrons and protons, seeding the formation of atomic nuclei. Within 300 seconds after the Big Bang, the very lightest elements—hydrogen, helium, lithium and beryllium—were formed. At that time, the formation of other chemical elements stopped and only started again once nuclear reactions ignited inside the first stars, some 100 million years later. All elements heavier than lithium were formed as stars burned their nuclear fuel, or in the violent environments of exploding stars—novae and supernovae—and colliding neutron stars. An ongoing line of research tries to determine the nuclear reactions that can occur in these different environments and drive the creation of the chemical elements we find around us.

An even more puzzling question arises from the observation that the universe appears to be made up only of matter. The Big Bang most likely created matter and antimatter equally. If this is true, there must have been a small difference—an asymmetry of one part in a billion—between matter and antimatter. Thus, when matter and antimatter annihilated each other as the universe cooled, a very tiny fraction of matter particles survived and make up our world today.

2. Why Do We Think a New Paradigm is Required?

Despite the great success the Standard Model has enjoyed when tested over the decades since its discovery, recent years have revealed signs of incipient failure. In particular, these new-found flaws indicate that it is very likely to be replaced at the distances that are just now becoming accessible at the highest-energy accelerators. The following paragraphs summarize the evidence for why a new theory is now required. Subsequent sections describe in more detail the role this evidence plays in guiding the ongoing research program worldwide.

a. Neutrino Oscillations.

Perhaps the clearest evidence to date for the Standard Model's failure is the discovery of neutrino oscillations. Decades of effort culminated in the 1990s with evidence of possible reactions that can turn electrons, muons and taus into one another through reactions involving neutrinos. This evidence came from neutrinos produced deep within the Sun and from neutrinos produced by cosmic rays in the upper atmosphere on Earth, followed later by experiments at accelerators. In essence, these observations imply that L_e, L_μ and L_τ are not separately conserved, most likely due to the presence of a nonzero neutrino mass. This requires moving beyond the Standard Model, and may have implications for cosmology (the study of the evolution of the universe as a whole) and astrophysics.

b. Dark Matter and Dark Energy.

Cosmology provides a second line of evidence that the Standard Model cannot be a complete description of nature. Although the Standard Model underpins the Hot Big Bang model, which provides a very successful description of cosmological observations, observations over recent years show that the Big Bang model only works if the universe is dominated by matter and energy that we do not yet understand. Modern surveys show that ordinary matter—described by the Standard Model—can make up at most about five percent of the total energy density in the universe. Although neutrinos and photons are currently the most abundant ordinary particles in the universe, it is ordinary atoms—mostly hydrogen—that dominate in the energy density because they are relatively heavy. The rest consists of two completely different, yet unknown forms of matter—for lack of better names, Dark Matter (about 25 percent) and Dark Energy (around 70 percent). Neither of these can be accommodated within the framework of the Standard Model together with general relativity, and so provide important evidence that something is missing. At present it is not known whether this involves some new kinds of particles or new interactions. One of the roles of subatomic physics is to figure out what this stuff might be.

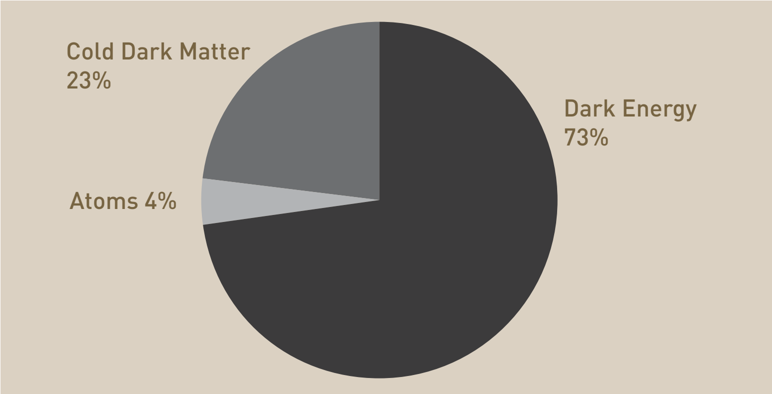


Figure 4: The distribution of matter and energy in the universe. We do not yet understand the nature of the cold dark matter, nor the dark energy.

c. Including gravity.

A third line of evidence for the incompleteness of our current understanding comes from the awkward co-existence between the Standard Model—describing the electromagnetic, strong and weak forces—and general relativity—describing gravity. Although experiments are not yet available that can probe gravity over the small distances for which quantum gravity is important, 50 years of theoretical research have proven it to be notoriously difficult to come up with any theoretical framework at all that can combine gravity with quantum mechanics in a sensible way.

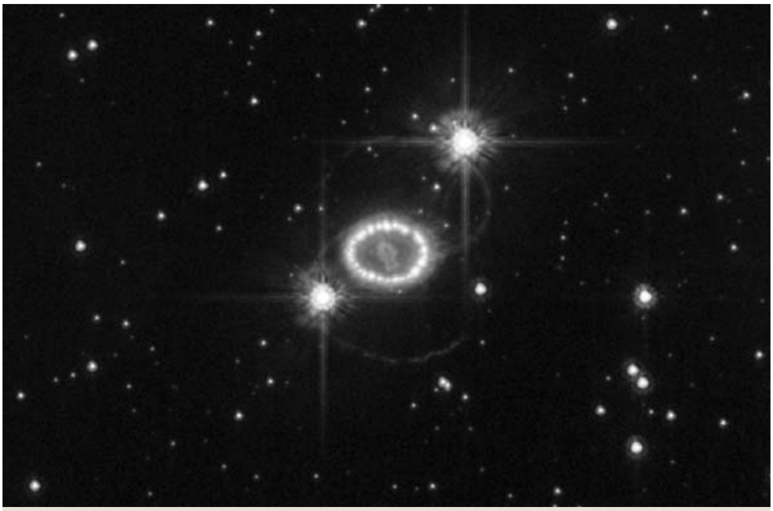
Very few theories have emerged over the years that can claim to have done so, and the best theory developed of these is the string theory. String theory proposes that the elementary constituents of nature are not particles at all, but rather strings—fundamental objects having a nonzero length, but zero width. Although the question remains as to whether or not string theory describes nature in any way, its tight mathematical structure has provided surprising insights into quantum field theory—the mathematics that is the language in terms of which our description of nature is cast.

3 The Global Program in Subatomic Physics

1. Introduction

We have developed our present understanding of nature at the subatomic level by performing experiments and placing the results in the context of theoretical models. Because the subatomic regime spans different distance and energy scales, a variety of particle types, such as electrons, protons and atomic nuclei, are employed in these experiments to further our knowledge. Many of the experiments manipulate particles with accelerator technology and essentially all use sophisticated particle detector technology. The particles may be trapped and "cooled" to the lowest energy achievable to study decays, or they may be accelerated to nearly the speed of light and collided in order to form new particles or types of matter. Experiments may be performed over time scales of decades, requiring thousands of scientists, engineers and technicians, or may be performed by several people within the span of a few days. Some studies must be performed deep underground in order to reduce backgrounds from cosmic and other radiation, while others specifically study cosmic radiation of different kinds. Theoretical calculations may require thousands of hours on the world's most advanced computers, while other advances may arise from the insight of a single person with pen and paper and a moment of genius. These different approaches to our science are complementary and are responsible for the tremendous advances that we have made in understanding nature.

The worldwide community has embraced a diverse approach to address the important questions in subatomic physics. Here we will describe how various accelerator, underground and cosmic approaches are used, and how the quest for understanding often requires that other key questions be answered first. We provide some examples of facilities around the world in order to place the Canadian program in the global context. Figure 5 illustrates the broad overlap between these different approaches. As noted earlier, the experimental work described here tends to be highly collaborative and is most often performed by large international teams working at complex facilities. Experimentalists are supported by a broad theoretical community, working at universities and laboratories worldwide.



Nuclear Astrophysics—an Example

The field of nuclear astrophysics can be used as an example of the interplay and complementarity of the different approaches. For example, astronomical observations use spectrographic data to determine the chemical abundances in stars, and these data are supplemented by cosmic gamma-ray measurements that are specific to particular isotopes. Theoretical modelling of the stellar environments uses knowledge of nuclear structure and predictions of reaction rates in an attempt to reproduce the abundances. The nuclear structure information is obtained over many experiments at both stable and radioactive ion-beam accelerators, and direct measurements of reaction rates are performed at these facilities including those housed in deep underground laboratories (to reduce backgrounds). As the nuclear physics information becomes more refined, the prediction of the environment in which such reactions take place becomes more certain.

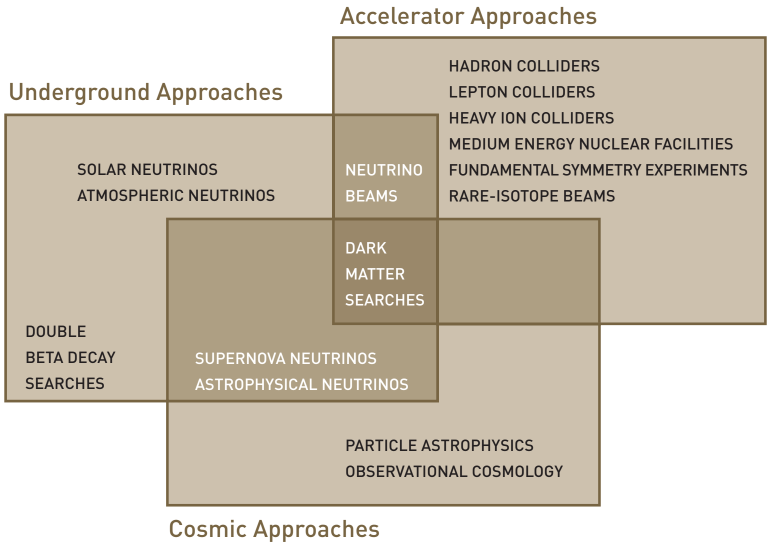


Figure 5: Three broad categories of experimental approaches—accelerator, underground, cosmic—are represented by the large rectangles. Specific physics programs are placed within these rectangles according to the experimental approaches that can be used to answer key physics questions. Some physics questions can be addressed by more than one approach and so they are included in the intersections of the rectangle regions.

2. Accelerator Approaches

Progress in accelerator technology over the past several decades has led to stunning advances in our understanding of subatomic physics. Particle beam experiments over a wide range of energies can explore physics of particles and nuclei on many scales. In general, the higher beam energies probe physics at smaller distance scales. However, experiments at lower energy can provide complementary information by increasing the precision of measurements or finding systems which naturally enhance properties of interest.

High-Energy Physics

For several decades, we have gained knowledge about fundamental interactions by accelerating particles to high energy and measuring what comes out of a collision. From accelerator programs around the world starting in the 1960s, we have learned of the existence of quarks, the "particle zoo," the unification of the electromagnetic and weak interactions, the properties of flavour, and much about the nature of the strong force. Recent advances have come from experiments undertaken at proton colliders—like the Tevatron at the Fermi National Accelerator Laboratory (Fermilab), and the Large Hadron Collider (LHC) at CERN—and at electron colliders—like the Large Electron Positron Collider (LEP) at CERN, and PEP-II at the SLAC National Accelerator Laboratory. Collisions of entire nuclei—such as in the Relativistic Heavy-Ion Collider (RHIC) machine at Brookhaven National Laboratory (BNL)—allow physicists to investigate properties of matter at extremes of pressure and density in order to study the phases of quantum chromodynamics (QCD), such as the existence in neutron stars or in the moments after the Big Bang.

The LHC at CERN is now the focus of world attention in particle physics. This machine collides protons and heavy ions, such as lead nuclei, at high energy and intensity—the proton-proton collisions will eventually reach 14 teraelectronvolts (TeV) center of mass energy. The LHC has four high-profile detectors designed to answer leading questions in subatomic physics. Two of these—ATLAS and the Compact Muon Solenoid experiment (CMS)—will have unprecedented capabilities for precision measurements of the known interactions and sensitivity to new physics. The Higgs boson—one of the key predictions of the Standard Model—is one famous quarry, yet to be hunted down. If the Higgs is not found, a dramatic new theoretical framework describing nature may be required; if it is found, its detailed properties will be studied. Other quarries include supersymmetric particles, possibly the unknown Dark Matter. A confirmed supersymmetric particle signature produced on the microscopic scale at a collider would have vast implications for understanding dynamics on the scale of the entire universe. LHC physicists are also searching for other new exotic particles, forces and extra dimensions, and the subatomic physics community is eagerly anticipating the results.

Next-generation electron colliders have recently been approved for construction in Italy and Japan to further understand flavour physics. In the future, a high-energy electron linear collider, like the International Linear Collider (ILC), may be built to further investigate new physics revealed by the LHC. The designs for such a collider, which may reach more than 30 kilometres in length, are nearing completion and could go forward later this decade.

Medium-Energy Facilities

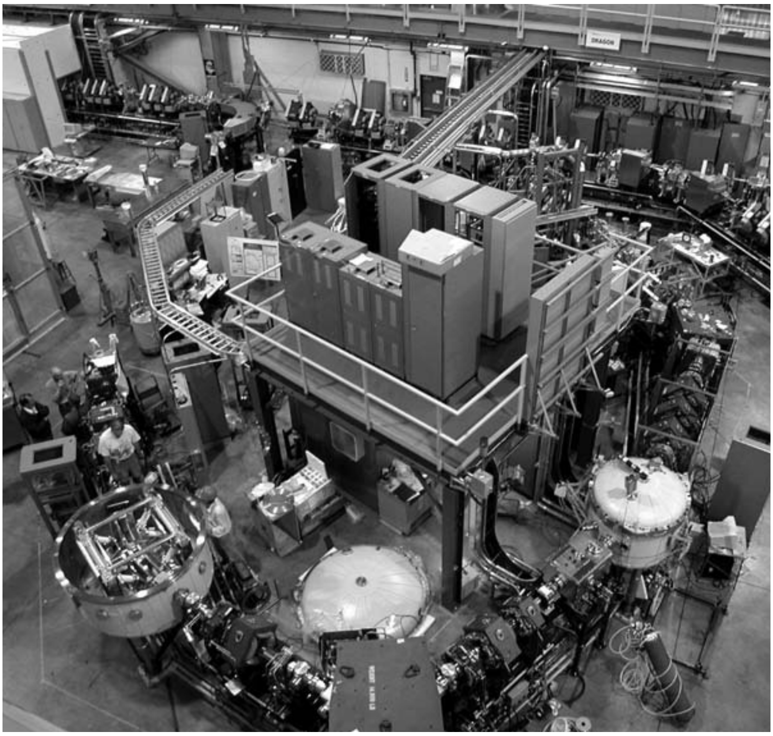
Experiments at medium-energy electron and hadron facilities are designed to provide understanding of the quarks and gluons and their motion within the nucleon, and understanding how QCD gives rise to the properties of the lighter hadrons and how these properties are influenced by the nuclear environment. These experiments at research facilities around the world make detailed comparisons with QCD predictions, to look for exotic forms of matter predicted by QCD—such as glueballs and hybrid mesons—and to gain a three-dimensional view of how quarks and gluons give rise to the observed properties of nucleons and mesons. One of the premier facilities to study the properties of hadrons is the Thomas Jefferson National Accelerator Laboratory (Jefferson Lab) in the United States of America (U.S.), where beams of electrons up to energies of 6 gigaelectronvolts (GeV) are scattered off nuclei. Complementing studies with electron beams are those that use real photons such as at the Mainz Microtron (MAMI) facility in Mainz, Germany. The recently completed upgrades at MAMI include a new accelerator with a 1.5 GeV electron beam together with a new polarized proton target and refurbished detector systems.

The Facility for Antiproton and ion Research (FAIR) at the GSI Helmholtz Centre for Heavy Ion Research (GSI) in Germany, the Japan Proton Accelerator Research Complex (J-PARC) in Japan, and the 12 GeV upgrade at Jefferson Lab are noteworthy new international projects that are designed to address these questions, and also fundamental symmetry questions, in detail. J-PARC has already commenced operations, while FAIR and the 12 GeV upgrade will begin operating during this five-year plan. FAIR will provide high-intensity antiproton and ion beams. J-PARC will provide intense proton beams up to 50 GeV in energy that can be used in experiments directly, or used to create intense secondary beams of neutrons, mesons and neutrinos from these mesons.

Rare-Isotope Beam Facilities

At lower energies, subatomic physics (here termed low-energy nuclear physics) enters the realm of composite particles—neutrons, protons—and their interactions, which lead to the formation and determine the structure of the nuclei that define most of the observable matter in the universe. Low-energy nuclear physics faces key questions such as how to describe the observed varieties of low-energy structures and reactions of nuclei in terms of the fundamental interactions between individual nucleons, and how to understand the evolution from single-particle properties to collective motion as functions of mass, isospin, angular momentum and temperature. Answering these questions has been facilitated by the development of a new theoretical paradigm for nuclear interactions that rests on understanding of the connectivity of the different size and energy scales involved. Advances in computational ability have enabled solutions of QCD appropriate for bound quark systems (the hadrons), and new effective field theories have made the connection between the QCD and the nucleon-nucleon potential. Finite nuclei can now be built using the nucleon-nucleon interaction in a systematic way—the so-called ab initio approaches—that have shown the importance of a consistent treatment of three-body forces and their influence on the properties of nuclei.

Complementing this new theoretical paradigm are advances in technology that create beams of unstable isotopes which allow for the direct study of nuclear reactions that are important to the understanding of the origins of the elements of the universe and of the nuclei that are involved in such reactions. Nuclear reactions occurring in stars are directly observed in satellite-based observatories and accurate abundance patterns can be observed throughout the history of the universe reaching back to the first stars. Rare-isotope beams are essential tools for unravelling the reaction rates in stellar burning and stellar explosions. The laboratory experiments using these beams provide the accurate nuclear physics that, combined with the observations, delivers the precision input needed for the computationally involved astrophysical simulations of the chemical evolution of the universe. We are entering an era where nuclear physics uncertainties are being reduced to the point where the conditions of the astrophysical sites are being constrained.



The DRAGON detector in the ISAC-I facility at TRIUMF

Rare-isotope beams are obtained by two complementary techniques, through the Isotope Separator On-Line (ISOL) process or through in-flight fragmentation of fast heavy-ion beams near relativistic energies. Future facilities for exotic rare-isotope beams provide stopped nuclides and beams with orders of magnitude-greater intensities than at present. These will allow experiments on rare and exotic nuclei, in which the number of neutrons or protons has been increased. The boundary of the region of possible nuclei is called the dripline; beyond that point no nucleus will even form. In these extreme configurations new phenomena—such as neutron halo and skin structures—are expected to occur. At present the neutron dripline has only been studied up to fluorine (Z=9); whereas the proton dripline on the other side of the valley of stability has been studied up to bismuth (Z=83). In addition to upgrading the present and building next-generation accelerator facilities, significant advances in experimental techniques are key to further progress.

New experimental approaches—such as the use of large gamma-ray tracking arrays, powerful high-transmission nuclide separators, advanced atom and ion traps, storage rings and laser spectroscopy, along with the exploitation of new types of reactions in inverse kinematics—such as knockout reactions and intermediate energy Coulomb excitation—are revitalizing experimental capabilities. Where once beams of at least 10 particles per second were standard, experiments can now be done with orders-of-magnitude lower beam intensity and, in selected cases, at rates even below one particle per day.

Canadian graduate student with the Qweak experiment at Jefferson Lab

The Canadian community plays a leadership role in the worldwide effort, taking full advantage of the fact that ISAC, at Vancouver-based TRIUMF, is the highest-power ISOL facility. This gives ISAC a major advantage for reaching the highest intensities for radioactive beams. The recently upgraded ISAC-II facility is currently the only one worldwide to provide accelerated rare-isotope beams at or above the Coulomb barrier over its entire production range of nuclei, including the heaviest species below uranium. In the future, a new 50 megaelectronvolts (MeV) electron linear accelerator (eLINAC), part of the ARIEL project, will provide a unique multi-user rare-isotope beam facility enabling long-term experiments with high discovery potential.

Worldwide, there are significant investments in this area of research with the construction of a new in-flight Facility for Rare Isotope Beams (FRIB) at Michigan State University, the ISOL facility SPIRAL-II in France, and FAIR, as well as with the operation of the Rare Isotope Beam Factory (RIBF) at RIKEN in Japan and the On-Line Isotope Mass Seperator (ISOLDE) facility at CERN.

High-Precision Approaches

High-precision experiments at lower energy can probe mass scales and couplings not accessible at the higher-energy facilities, and provide crucial information about any new particles that may be observed at the LHC. For example, the Qweak experiment in progress at Jefferson Lab scatters electrons off protons to measure weak interaction parameters using parity violation, while the future MOLLER experiment at the same laboratory will determine the electron weak charge to high precision and have unparalleled sensitivity to new electron-electron (e-e) interactions, probing electron substructure. These measurements will be complemented by parity violation studies in atomic systems, such as the work with cold-trapped francium atoms under development for TRIUMF-ISAC, and measurements of rare kaon decay modes and the muon magnetic moment planned for Fermilab's Project-X. The ALPHA and ATRAP experiments at CERN will search for differences in the spectroscopy of hydrogen and antihydrogen, directly testing CPT conservation. In hydrogen these are among the most accurately measured properties in physics.

New interactions that do not behave in the same manner when the direction of time is reversed are necessary to explain the imbalance of matter and antimatter in the universe. Subatomic physicists are seeking to detect time-asymmetric forces through precision measurements of the properties of the neutron, atoms and mesons. Several planned experiments with ultra-cold neutrons will search for the neutron electric dipole moment (EDM) which would imply a violation of time-reversal symmetry; a joint project undertaken by physicists in Canada and Japan aims to conduct a world-leading search at TRIUMF. Similar experiments seeking EDMs using nuclear isotopes with octupole deformations are expected to be particularly sensitive. Some of the most favorable cases involve the odd-A radon isotopes, studies of which are planned for TRIUMF-ISAC. Technologies with cooled and trapped atoms also enable fundamental symmetry studies, and the TRIUMF Neutral Atom Trap (TRINAT) experiment will tackle properties of nuclear beta decay, sensitive to sources of time-reversal violation relatively unconstrained by EDM experiments, while at J-PARC the TREK experiment will perform a time-reversal violation test in kaon decay.

Accelerator Development

Accelerator R&D is crucial if the above goals are to be attained. In the past decade, there have been tremendous advancements in accelerator technology for electron, hadron and rare-isotope beam production. The most successful accelerator laboratories, like TRIUMF, have intensive R&D efforts that directly support their missions. Technology transfer amongst the laboratories ensures that each benefits from the latest developments and many, like TRIUMF and India's Variable Energy Cyclotron Centre (VECC), have formed partnerships for further research. The ARIEL accelerator project at TRIUMF, based on 1.3 gigahertz (GHz) superconducting radio-frequency (RF) technology, will be used to produce high-intensity rare-isotope beams from photo-fission and will demonstrate the technology that may be used for the International Linear Collider. R&D related to rare-isotope facilities also includes essential development work on ion sources, separators, targets, and remote handling of complex target modules containing highly radioactive materials.

3. Underground Approaches

Deep, underground laboratories provide an essential venue for shielding sensitive experiments from cosmic radiation that continuously bombards the surface of Earth. Several underground facilities exist around the world, including in Canada, the U.S., Japan, Italy, France and China. SNOLAB in Canada is a premier international laboratory.

Neutrinos

Knowledge of the properties of neutrinos is essential to the understanding of fundamental physics, as well as astrophysics and cosmology. The flavour change (oscillation) of neutrinos, which implies that they have non-zero mass, was first observed by Super-Kamiokande (Super-K). The Sudbury Neutrino Observatory (SNO) experiment then determined unambiguously that neutrinos from the sun are transforming flavour. KEK to Kamioka (K2K) in Japan and the Main Injector Neutrino Oscillation Search (MINOS) in the U.S. made the first "long baseline" neutrino oscillation measurements, observing the flavour change of high-intensity neutrino beams sent over long distances.

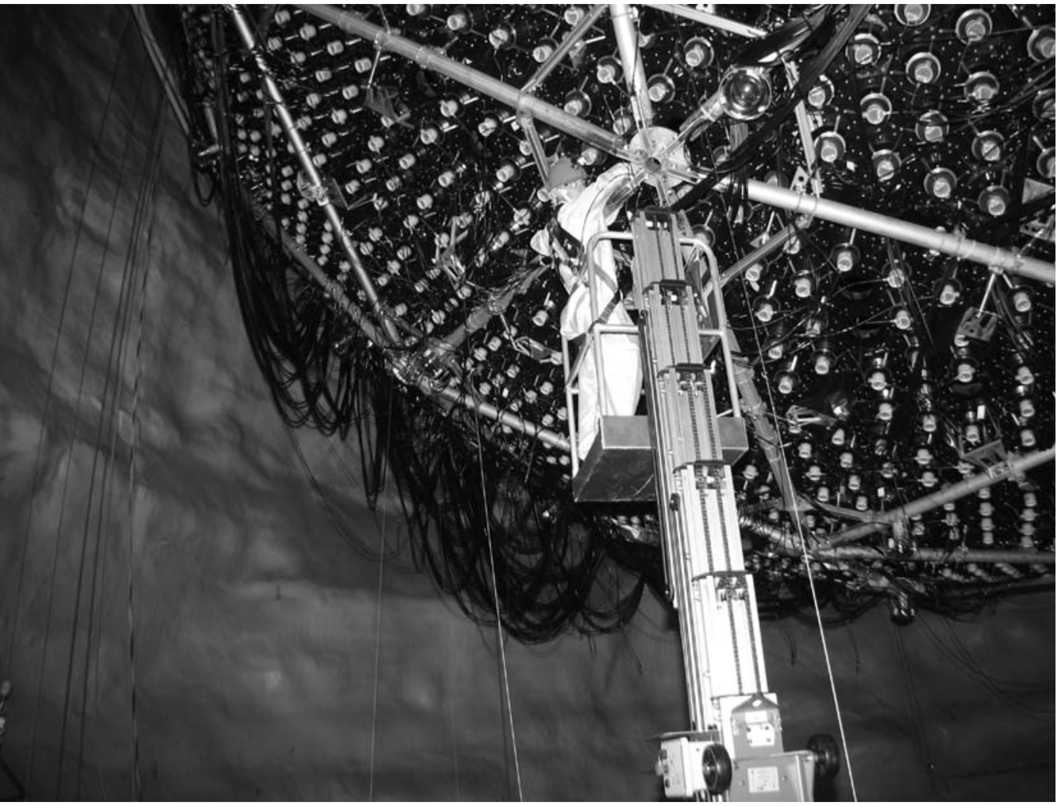
Neutrino physics questions can be addressed with both accelerator and underground approaches. Neutrinos can be created with accelerators, but they are also produced by cosmic rays, by stellar fusion reactions and by astrophysical sources such as supernovae. Because neutrinos are so weakly interacting, neutrino experiments must very often be done underground to shield them from cosmic rays.

The new generation of neutrino oscillation experiments, including some observing nuclear reactor neutrino fluxes, and high-intensity beam experiments such as T2K, will hunt down the unknown parameter describing neutrino oscillation—termed θ_{13}—over the next few years. Future phases of these experiments will search for an asymmetry between neutrinos and antineutrinos, which may provide clues to the overall mystery of matter-antimatter asymmetry. Ambitious neutrino programs are planned worldwide, involving both high-intensity beams and very large detectors.

Low-Background Experiments

In addition to protection from cosmic rays, some experiments hunting for extremely rare processes require environments with very low levels of radioactivity. SNOLAB is unique in its great depth and low level of radioactive background and can satisfy both requirements.

Among experiments requiring low background and deep sites are those searching for exotic radioactive decays (beta decays involving emission of two electrons simultaneously but without neutrinos). Observation of these will give insight into neutrino absolute masses and the question of whether the neutrino is its own antiparticle—essential information about the basic nature



Upgrading the SNO detector for the SNO+ experiment

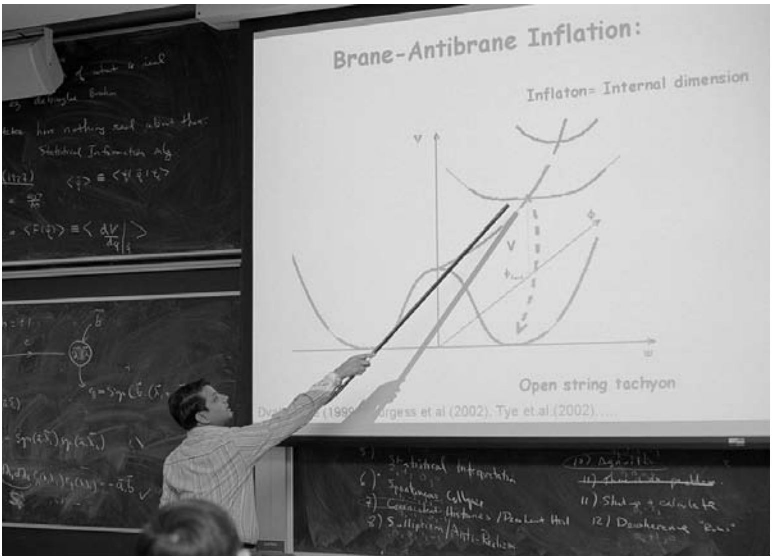
of matter that is necessary if we are to understand the history of the universe. Several experiments worldwide are searching for the signature of this special decay, including SNO+, Majorana and EXO.

Experiments that search for Dark Matter through their tiny nuclear recoil signals demand very low radioactivity environments. There is a very broad, technologically diverse and competitive worldwide program of such experiments, including the Cryogenic Dark Matter Search (CDMS), Dark Matter Experiment using Argon Pulse-shape discrimination (DEAP), Cryogenic Low Energy Astrophysics with Noble gases (CLEAN), Project in CAnada to Search for Supersymmetric Objects (PICASSO), and the Chicagoland Observatory for Underground Particle Physics (COUPP).

4. Cosmic Approaches

The last few decades have seen a variety of questions arise at the intersection of particle physics and astronomy, spawning the interdisciplinary field of particle astrophysics worldwide. Information from each field is helping to solve problems in the other.

The most violent particle collisions known occur in outer space and they bombard Earth with a variety of cosmic particles, from protons and gamma rays to neutrinos and other particles. Their detection provides a wealth of information about the astronomical furnaces in which they are forged, about the environment through which they pass en route to us, and about the nature of the particles themselves.



Joint Perimeter Institute—Canadian Institute for Theoretical Astrophysics Workshop

For instance, neutrinos produced by stellar explosions—supernovae—teach us about both neutrino oscillations and the physics of the extreme environment of the supernova explosion. Vast, cubic-kilometre-scale photosensor array experiments under ice or water—such as IceCube and Antares—search for high-energy neutrinos from cosmic sources. Cosmic radiation—mostly ordinary particles like protons, nuclei and photons—tell us about exotic distant objects, the presence or absence of particles or fields in the foreground, and potentially about the properties of Dark Matter. Our efforts to explain the observations made by particle astrophysics will test our understanding of fundamental physics.

Cosmology—the study of the universe as a whole—represents another area of contact between particle physics and astronomy, in particular providing evidence that 95 percent of the universe is unknown to us—Dark Energy (70 percent) and Dark Matter (25 percent). Understanding these is the job of particle physics, and much effort is devoted to developing and testing theories for what they might be. This involves identifying connections between astronomical observations of distant supernovae, galaxy clusters and the Big Bang's residual glow—cosmic microwave background radiation—and terrestrial experiments like Dark Matter detectors, accelerator experiments, precision tests of conservation laws, etc.

5. Theory

All of the experimental techniques discussed above are dependent upon close interactions between the experimental and theoretical subatomic communities. Theoretical subatomic physicists study and develop the theoretical framework and mathematical tools to understand current experiments, make predictions for future experiments, and try to understand the overall structure of our knowledge of nature at subatomic scales. The vitality of the field of subatomic physics depends on the vibrancy of both of these communities: theoretical ideas motivate new experiments and are needed to interpret experimental signals, while experiments in turn are required to test theoretical ideas.

Theoretical subatomic physics covers a large realm of inquiry, from the highly abstract and speculative to direct calculations of experimental predictions, and from nuclear distances down to scales presently beyond experimental reach. Broadly speaking, nuclear theory is concerned with the collective behavior of nucleons, while particle theory is concerned with phenomena on subnuclear scales. But this distinction is not always crisp, as fields such as lattice QCD and heavy-ion physics are of interest to both communities. Subatomic theory also has ties to related fields, such as atomic and condensed matter physics, astrophysics and cosmology, and pure mathematics.

Another way to slice the theory effort is to distinguish between formal research and phenomenological research, where the distinction indicates the extent of the direct relevance to current or near-future experiments. But even here the distinction is not always clean. For example, in recent years very formal advances in quantum field theory have been found to have surprising applications to calculations useful for collider physics. It is these kinds of deep and unexpected connections that reward supporting theory not directly tied to the experimental effort.

The importance of the interplay between theory and experiment is demonstrated by the fact that all large international laboratories—including CERN, SLAC, BNL, Fermilab, Jefferson Lab, TRIUMF, Kou Enerugi Kenkyu Kiko (KEK), and Lawrence Berkeley Lab—have significant theory groups. Furthermore, while these theory groups certainly provide significant support to the corresponding experimental programs, these international labs typically do not restrict their theory groups only to areas narrowly tied to their experimental programs. In part, this is because, as a group, theorists can change their research direction much more quickly than can experimental groups.

4 The Canadian Science Program: Present and Future

The Canadian subatomic physics program is designed to maximize scientific output and impact on a global stage. Strategic choices have been made that allow us to focus our efforts and stake-out a clear Canadian role, whether the experimental facility is in Canada or abroad. These choices have been made in wide consultation with the Canadian subatomic physics community through processes similar to the one that produced this document and, more regularly, through the national organizing bodies, the Canadian Institute for Nuclear Physics (CINP) and the Institute of Particle Physics (IPP).

In cases where world-leading domestic facilities exist, the Canadian community has naturally coalesced to exploit these investments. The ISAC facility at TRIUMF is the highest power isotope separation on-line facility in the world. Ensuring that this world-leading facility produces world-leading science requires experiments conducted by world-class researchers. ISAC attracts these researchers from within Canada and internationally. Similarly, over the past 10 years Canada has built one of the world's premier underground laboratories—SNOLAB. The Canadian neutrino and dark matter search communities have flocked to SNOLAB, and the world is following suit. The past 10 years have also seen the building of the Perimeter Institute (PI)—one of the leading theoretical physics institutes in the world. PI brings some of the brightest members of the world subatomic theory community to Canada.

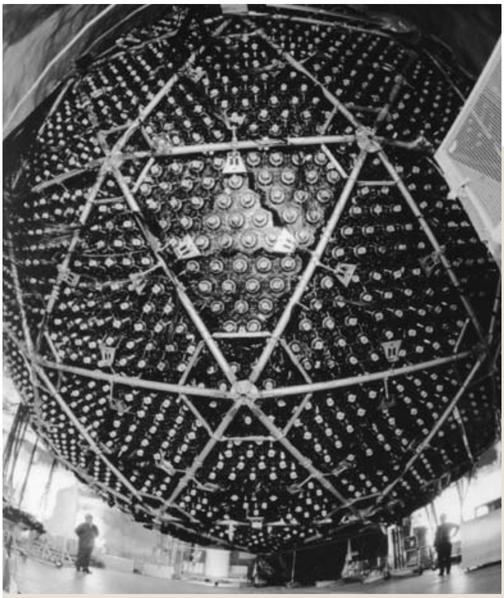
The scale of the projects on which we work makes it impossible for Canada, or any country, to host the elite international facility in every aspect of subatomic physics. Therefore, just as researchers from around the world make extensive use of ISAC and SNOLAB, Canadian researchers travel abroad to take advantage of leading facilities in other nations. In these cases, we have also made strategic choices and investments. For example, at the LHC there are four major experiments. However, the Canadian effort has coalesced

around a single multi-purpose experiment—ATLAS. We are one of the founding nations in the ATLAS collaboration. This magnifies Canadian impact and puts a "made-in-Canada" stamp on our significant contributions to this project. A second example arises in long-baseline neutrino experiments. Canada has focussed its effort on T2K in Japan, rather than be split across multiple facilities. Accordingly, we comprise more than 10 percent of that collaboration and play a leading role in many aspects. A third example comes from Jefferson Lab in the U.S. The world hadronic structure community has itself coalesced at this premier facility. Canadians have been active at Jefferson Lab for 20 years and have contributed significant leadership to key parts of its scientific program. These three examples illustrate the international scientific partnerships subatomic physics has built between Canada and Europe, Japan and the U.S., respectively. As will be explored further in later sections of this report, these partnerships have benefits beyond the science. They benefit Canadian industry and the training of Canadian students.
The following section highlights some of the accomplishments of the Canadian community over the past five years, details the ongoing program expected to yield results in the next five years, and looks ahead to long-term opportunities for Canadian subatomic physics.

1. Accomplishments: The Past Five Years

The last five years have seen key results from research in the Canadian subatomic physics program. The SNOLAB facility has been constructed and is now the site of several new experiments. Construction was completed on T2K and the experiment has started to take neutrino oscillation data and has published its first analysis. ATLAS has been commissioned and first results have been reported. At TRIUMF, the ISAC-II accelerator was commissioned along with major new spectrometers—TRIUMF-ISAC Gamma-Ray Escape-Suppressed Spectrometer (TIGRESS) and TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN)—and experiments making use of these instruments are ongoing.

A view of the Canadian-built ATLAS Hadronic Endcap, prior to installation



Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) was built by a Canadian-U.S.-United Kingdom (U.K.) collaboration in the Vale-Inco Creighton Mine outside Sudbury. The detector consisted of 1,000 metric tonnes of heavy water contained in a 12-metre radius acrylic sphere and observed by 10,000 20-centimetre photomultiplier tubes. Neutrinos are copiously produced in the sun, and the flux of neutrinos at the Earth is about 10 billion per square centimetre, per second (about two percent of the Sun's energy). These neutrinos travel freely through the Sun and the Earth, but a small fraction (about 20 per day) interacted inside the SNO detector. Three different neutrino reactions occur in heavy water, and distinguishing between these reactions allow us to measure the total number of neutrinos, and provides information about types of neutrinos.

The fusion reactions in the Sun only produce electron neutrinos; however, SNO showed that two-thirds of the neutrinos reaching the detector were mu-neutrinos or tau-neutrinos. This means that neutrinos change type (or "oscillate"), which points to new physics beyond that described in the Standard Model.

SNO took data between 1999 and 2006 in three different configurations that counted the total number of neutrinos in three very different ways. The initial measurements were published in 2001, but continued work has significantly heightened its original precision by improving upon the calibrations and combining the data from the three phases of the experiment. Final publications are expected in 2011.

At the time of the last subatomic physics long-range plan (LRP) report, the Canadian particle physics community was actively engaged in the collection and analysis of data from the SNO experiment, the B-Bbar detector (BaBar) experiment at SLAC, the Collider Detector at Fermilab (CDF) and D0 experiments at Fermilab, and ZEUS at Deutsches Elektronen-SYnchrotron (DESY), and a host of smaller projects. In addition, construction and installation of the ATLAS detector at CERN was well underway and the construction of T2K had started. The nuclear physics community was mounting strong experimental programs involving hadronic structure at the 6 GeV accelerator at Jefferson Lab, and was working on the weak interaction measurements and nuclear astrophysics at TRIUMF. In the past five years, significant progress has been made and the accomplishments of the Canadian community have been remarkable.

Canadian participation in the CDF and D0 experiments at Fermilab has drawn to a successful conclusion, as experimentalists have now shifted their focus and efforts to the new energy frontier at the LHC. Canadians have been instrumental in many of the key physics results to emerge from the Tevatron in recent years, including the first observation and subsequent measurement of single top quark production and the first direct measurement of the coupling of the top quark to a W boson. Members of the Canadian CDF group led the precise CDF W boson and top quark mass measurements, and also contributed substantially to direct searches for the elusive Higgs boson. These key electroweak and flavour physics measurements strongly constrain the Standard Model and set the stage for new physics searches at the energy frontier at the LHC.

Substantial progress has been made in our understanding of flavour physics, the mixing of quarks via the weak interaction. SLAC's B-factory completed its data-taking phase in 2008, bringing to an end the Canadian operational responsibilities for the large volume drift chamber, constructed at TRIUMF, which was the core of the Canadian detector contribution to the BaBar experiment. A strong Canadian presence in the collaboration has continued, with key contributions and leadership by Canadians in many of the most active areas of physics analysis, and in the overall leadership of the project. The success of the experimental program to understand flavour physics was acknowledged by the Nobel Committee in 2008, with the shared award of the Nobel Prize in Physics to Makoto Kobayashi and Toshihide Maskawa for their explanation of the mechanism for CP violation within the Standard Model. Experimental verification or refutation of the Kobayashi-Maskawa mechanism was the primary purpose of BaBar. With this objective successfully achieved, these same decay modes can then be used as precision probes of possible physics beyond the Standard Model, complementing the direct energy frontier searches performed at the Tevatron and now also the LHC. Moreover, experience gained on the BaBar experiment is paving the way for the next generation of ultra-high luminosity B factories in Italy and Japan.

Major Canadian involvement in detector installation and commissioning activities for the LHC culminated in the first high energy data taking for the ATLAS experiment in 2010. ATLAS-Canada has successfully delivered on its major hardware construction and commissioning projects, and in the first period of data taking the Canadian forward and hadronic endcap calorimeters have operated according to design expectations and with near-perfect operational efficiency. The Tier-1 ATLAS computing centre at TRIUMF was successfully commissioned and is currently fully operational, hosting primary and derived data and ATLAS simulation. It regularly ranks among the top in the world, delivering 99 percent availability for 24 hours a day, seven days a week (24/7) operation during ATLAS data-taking. Canada also hosts four regional Tier-2 computing centres distributed throughout the country. These centres have been realized using CFI funds either directly, in the case of the Tier-1, or indirectly via Compute Canada for the Tier-2's. A first ATLAS physics analysis was published on charged particle multiplicities in 900 GeV data in early 2010 and first 7 TeV physics results were presented with much interest at the 2010 International Conference on High Energy Physics (ICHEP), including not only physics validation and Standard Model measurements, but also the first results of exotic searches with sensitivity exceeding that of the Tevatron. Indeed, at the European Physical Society (EPS) 2011 conference, both ATLAS and CMS already showed sensitivity to the Higgs boson over a wide range of possible masses. They each excluded new Higgs mass ranges and were investigating statistically insignificant but intriguing excesses at the time of writing. These new results usher in an exciting and much anticipated new era of physics exploration at the LHC. Canadians were not only lead analysts and authors in this effort, but also contributed to many of the specific collaborative analysis activities, including data calibration and particle reconstruction efforts, that make these seminal results possible.

Data acquisition at the Canadian-based SNO ended in November 2006, following the third phase of operations. Analyses of the three phases were done separately, allowing SNO to show a consistent picture of solar neutrino flux and oscillations through very different measurements. In addition, by combining several phases in analyses, significant improvements in both statistical and systematic uncertainties were seen. Continued improvements in the analysis allowed SNO to reanalyze previous data with greatly improved precision. These measurements conclusively demonstrated that solar neutrinos oscillate on their way from the core of the Sun to the Earth, thus resolving the long-standing solar neutrino problem and proving that neutrinos have mass. The core publications of the SNO collaboration have generated more that 4,500 citations. The SNO detector ceased operation in 2007, but the infrastructure contained in the SNO detector is being given new life as part of the SNO+ project in the new SNOLAB facility.

BaBar

The BaBar experiment at the SLAC National Accelerator Laboratory recorded collisions of electrons and positrons at an energy of 10.5 GeV—equivalent to about 10 times the mass energy of a proton—between 1999 and 2008. BaBar investigated not only the nature of CP violation in B meson decays, but also a large variety of other topics in heavy quark physics, providing indirect probes on possible new physics at very large mass scales. BaBar contributed to the 2008 Nobel Prize in Physics by providing the experimental confirmation of the predictions of theorists Makoto Kobayashi and Toshihide Maskawa regarding the nature of the weak interaction and matter-antimatter asymmetry. BaBar is an international collaboration of approximately 600 physicists from research institutions in 12 countries. Canadian groups participated in the construction and operation of the main charged particle tracking system for BaBar, and led data analysis efforts in several key areas of the physics program.

Indeed, the construction of SNOLAB was completed, experiments were installed and data began to flow. The first example is PICASSO—a Canadian-led and largely Canadian funded search for Dark Matter that uses superheated liquid detector technology. The analysis of a first set of two out of 32 new generation detectors resulted in the world's best limits. This analysis is presently being extended to the remaining 30 detectors that were operated in 2009-10 and new results are expected soon.

A new generation of neutrino experiments is now seeking to understand the nature of the mixing in the neutrino sector. To that end, Canadians have actively contributed to the T2K experiment with responsibility for the near-detector tracker, consisting of fine-grained scintillating detectors and large-volume time projection chambers, and an optical transition radiation beam monitor for the primary proton beam. R&D activities for these detector components were in the early stages at the time of the last LRP exercise, but they were subsequently designed, constructed, tested in TRIUMF's M11 beamline and ultimately installed and commissioned in 2009. The T2K experiment completed its first data run in 2010. The first publication from T2K, based on this data and released in 2011, has given the first indication that muon-neutrinos oscillate to electron-neutrinos. Canada is now one of the largest groups in T2K, totalling more than 10 percent of the collaboration, with a strong presence in analysis leadership roles. Canadian scientists are now extremely well positioned to lead the way in this exciting area of research.

The TRIUMF Weak Interaction Symmetry Test (TWIST) collaboration has completed the most precise measurement of the muon decay distribution. This allows TWIST collaborators to derive the electroweak coupling constants which determine the underlying symmetries of the theory. Extensions to the Standard Model, such as left-right symmetric theories, assume that right-handed particles also respond to the weak force, but at a much different energy scale. The TWIST results for the muon decay parameters have set the most stringent limits to date for left-right symmetric models, making it far less likely that these theories are the correct extension to the Standard Model.

In a wonderful example of how smaller-scale physics opportunities with discovery potential can emerge over the course of a five-year plan, we note that the Antihydrogen Laser PHysics Apparatus (ALPHA) collaboration has successfully trapped an ensemble of antihydrogen atoms as a first step in using these atoms for precision tests of CPT violation. This success was highlighted by *Physics World* as one of the top physics achievements of 2010.

Jefferson Lab currently provides 6 GeV electron beams of unprecedented quality and stability and is the world's pre-eminent facility in electromagnetic physics. Canadian use of this facility spans a 20-year period, and recent Canadian accomplishments demonstrate a very high scientific impact. In the recently completed G-Zero experiment, parity-violating electron scattering was used to infer that strange quarks make small (less than 10 percent) contributions to the basic properties of the proton, such as its magnetic moment and electric charge distribution. The Qweak experiment—the first-ever measurement of the weak charge of the proton—is now taking data following the commissioning of the Canadian-funded solenoidal spectrometer. The doubling of the Jefferson Lab energy to 12 GeV (with the delivery of the first beam in 2013) is designed to further our understanding of the transition between the hadronic and quark-gluon degrees of freedom in nucleons and nuclei. Canadians are on the frontline and carrying spokesperson responsibilities for two "A"-rated approved experiments—GlueX and the pion form factor—and providing hardware contributions to Halls C and D.

During the past five years, the ISAC facility at TRIUMF has successfully made the transition from construction to utilization. The ISAC-II accelerator for radioactive ion beams was commissioned, and initial experiments have used accelerated beams with atomic numbers $A<30$. The TIGRESS γ-ray spectrometer and TITAN mass measurement facility were completed and are performing experiments, and substantial improvements to a number of other spectrometers have been made. The experimental program at TRIUMF-ISAC takes advantage of these developments in instrumentation and uses the world-leading intensities to perform experiments that cannot be pursued at other facilities.

The experimental program using radioactive beams has an impact on many of the fundamental questions. The nature of the weak interaction has been stringently tested by the TRINAT facility and the 8π gamma ray spectrometer. These measurements support the Standard Model descriptions of the weak force and the couplings between the light quarks. The data strongly constrained the possibility of additional quark generations.

In the area of nuclear structure, significant new results have been obtained using both the accelerated beams with ISAC-II, and low-energy beams at ISAC-I. The nature of so-called halo nuclei, where the spatial extent of the outer neutrons greatly exceeds that of the rest of the nuclear matter, have been probed in reactions involving radioactive helium, lithium and beryllium beams at ISAC-II, and with measurements at ISAC-I. Experiments have commenced that test the nature of the interaction of proton and neutrons in the nucleus and how collectivity develops. Recent theoretical developments have also provided, for the first time, a method to solve the equations governing collective behaviour in the nucleus, providing clear guidance for experiments.

Tevatron

The CDF and D0 experiments for the Tevatron at Fermilab, near Chicago, recorded the collisions of protons and antiprotons at the highest energies accessible prior to the start-up of the LHC at CERN, approximately 2 TeV. CDF and DO are general-purpose experiments, designed to be able to study the broad range of physics accessible at these energies—from the basic properties of light quark interactions and B meson physics, to precision measurements of heavy $W^{\pm}$ bosons and top quarks, to searches for Higgs bosons and new particles at the highest accessible mass scales. Both experiments are operated by large international research collaborations which include Canadian groups. Canadian participants in the CDF collaboration played leading roles in the flagship $W^{\pm}$ boson and top quark mass measurements and contributed substantially to the high profile Standard Model Higgs search.

TRIUMF is already recognized worldwide for its direct measurements of nuclear reactions important in cataclysmic binary systems. Highlights from the Detector of Recoils And Gammas Of Nuclear reactions (DRAGON) include the measurement of a key radiative capture reaction with a radioactive beam, $^{21}Na(p, \gamma)^{22}Mg$, and the determination of the weakest resonance strength ever measured in inverse kinematics with a radioactive beam. Indeed, of the six radiative capture measurements ever made with radioactive beams, three were performed at TRIUMF using the DRAGON spectrometer. All of these reactions are related to the production or destruction of γ-ray emitters in classical novae.

2. The Canadian Program: 2011-2016

The strategic investments made over the past 10 years have well-positioned Canada. Many important projects have moved from construction and commissioning to physics. The Canadian community is set to reap the scientific rewards of these investments.

The subatomic physics community in Canada is comprised of both nuclear and particle physicists. While these two communities have much in common, the way in which experimental work is organized in each is somewhat different. Particle physics is often characterized by large collaborations operating single detectors continuously in order to perform a multitude of measurements. In some cases, data for many independent measurements are collected simultaneously and separated after the fact. On the other hand, the nuclear physics community is more likely to build a specific detector which can be used in a multitude of individual experiments, run sequentially.

These different ways of organizing the experiments are reflected in the presentation of this section. For example, ATLAS is presented as a single project in spite of the fact that it supports an extremely diverse set of studies which address many different aspects of the fundamental questions in particle physics. In contrast, the Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) spectrometer is mentioned in a number of places throughout this section in the context of individual nuclear physics experiments which will make use of the device.

a. The Energy Frontier

Accelerator Approaches at High Energy: ATLAS at the LHC
The LHC and the ATLAS detector have now moved from commissioning to physics. As the first collisions were observed in the ATLAS detector, millions of people around the world watched, fascinated by the scale and scope of this experiment. By the end of 2012, it is anticipated that there will be enough data from its current operation to make a definitive statement about

the existence of the Standard Model Higgs boson. There will also be enough data to either discover, or significantly constrain, many popular extensions of the Standard Model. After 20 years of planning, designing, and building the ATLAS detector, Canadians will spend the next five years reaping the harvest. Extensive knowledge will be produced, addressing some of the central questions the LHC was built to answer.

Canada's faculty-level commitment to ATLAS has nearly doubled since the last LRP exercise, exactly as anticipated, and Canadian researchers and their students and postdoctoral researchers are authors on ATLAS publications. The contributions of Canadian subatomic physicists are also being recognized within ATLAS by their selection for prestigious talks and coordination roles. ATLAS-Canada faculty, students and postdoctoral researchers are actively engaged in many leading-edge analysis efforts covering the spectrum from Standard Model measurements to the search for the Higgs boson, supersymmetry and other exotica.

Although verifying the origin of mass is often touted as the flagship physics of the LHC, it should be noted that ATLAS is making measurements that are sensitive to new physics such as the search for extra dimensions, compositeness, rare heavy-quark decays with muons and/or photons in the final state, and measurements of CP violating parameters. ATLAS is, in some sense, an experimental facility enabling a wide range of physics measurements and searches to be performed.

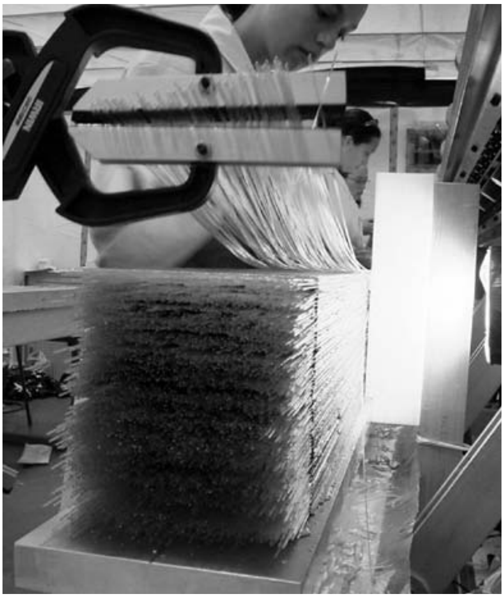
The results achieved by the ATLAS experiment during the current planning period have the potential to impact many areas of investigation in subatomic physics. For example, the scope of LHC upgrades or the design of a future linear collider depend on what is found in the next five years at ATLAS. The results obtained during this planning period could be revolutionary for our field.

b. The Organization of Nuclear Matter and the Origin of the Elements

Accelerator Approaches at Medium Energy: Jefferson Lab

At Jefferson Lab, Canadians are spokespeople for two major experimental initiatives in hadronic physics that will use the 12 GeV electron beam—the GlueX experiment and the F_π -12 experiment. The GlueX experiment will seek the existence of so-called "exotic hybrid mesons" by determining their unique quantum numbers, and will measure their masses and decay channels. The exotic mesons serve as sensitive tests of our understanding of QCD in the non-perturbative regime.

One of the most critical detector components—the Barrel Calorimeter—is in the final stages of construction in Regina, Canada.



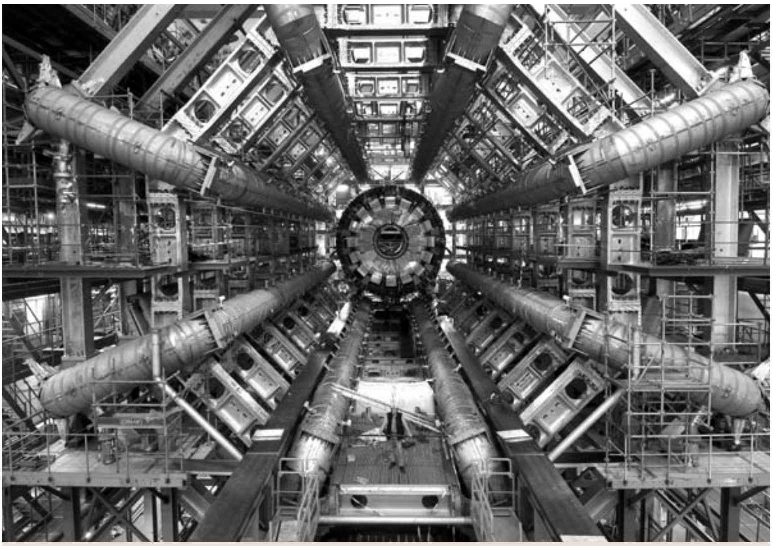
Scintillating fibres for the barrel calorimeter on the GlueX detector

A high priority is the development of a quantitative understanding of how quarks and gluons give rise to the observed properties of nucleons and mesons. The F_{π} -12 experiment will measure the structure of the pion at small-distance scales. The so-called pion form factor is typically one of the first observables that are compared with QCD calculations because of its importance in understanding the transition from short- to long-distance scales.

Rare Isotope Beam Facilities: TRIUMF-ISAC

The Canadian community is heavily engaged in probing the structure of nuclei, addressing the questions of the limits of nuclear existence, the evolution of nuclear shells and properties as a function of proton and neutron number, and the nature of collective excitations. All of these questions involve a synergy between experimental and theoretical developments. While most of the community performs the work at the TRIUMF-ISAC facility, there are also important contributions from offshore facilities.

As the nuclear physics community works through the new paradigm for effective interactions between nucleons, and the related calculation streams, it is critical to have robust experimental data in order to accurately predict the limits of nuclear existence, particularly for neutron-rich nuclei. Knowledge of nuclear masses provide a direct constraint, especially in extrapolating the limit for heavy nuclei. The Canadian mass measurement program is centred on the use of the TITAN facility at TRIUMF-ISAC. With the commissioning of the actinide target at TRIUMF, TITAN will be focussing on mass measurements of neutron-rich nuclei in the near future. In order to determine the evolution of the nuclear properties as a function of neutron and proton number, especially the locations of the nucleon orbitals, 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.



ATLAS

The LHC has redefined the energy frontier. Proton-proton collisions are ongoing at an energy of 7 TeV (3.5 times the Tevatron energy), with plans to ramp up to 14 TeV over the course of this planning period. This new energy regime, and the unprecedented volume of data, will allow us to probe for "new physics" well beyond the current limits.

Canada has been engaged in ATLAS—one of the flagship experiments at the LHC—since its inception. We have led the design, building and commissioning of key elements of the ATLAS detector—the hadronic endcap and forward calorimeters. We have also made significant hardware contributions to the ATLAS trigger and to the worldwide ATLAS computing grid through a national Tier-1 center at TRIUMF and major analysis facilities at five Canadian universities.

Now that the ATLAS experiment is built, and the basic commissioning is complete, the Canadian community is using it as a platform that enables a wide variety of research efforts across the country. Direct searches for new physics are well underway and Canadian-led analyses have already ruled out some possibilities. By the end of 2012, ATLAS will have accumulated enough data to answer some of the key questions facing the field. Toward the end of the planning period, data collection at 14 TeV should be well underway. This period is when Canada, and the world, reaps the scientific rewards for our investments in ATLAS.

The rich variety of collective excitations that nuclei display are examples of emergent phenomena that would not have been predicted even with complete knowledge of nucleon-nucleon force. However, we still do not have a fundamental understanding of how nuclei manifest collective phenomena nor of how these excitations evolve especially into the region of neutron excess. These excitations very often form the lowest excited states in nuclei, and thus are crucial in understanding nuclear properties. Detailed spectroscopic investigations are planned for experiments at the TRIUMF-ISAC and ISAC-II facilities. In this regard, the continued development of the actinide target and, in the future ARIEL beams, are especially important as they will provide the neutron-rich rare isotope beams required. The TIGRESS, GRIFFIN and ElectroMagnetic Mass Analyzer (EMMA) spectrometers with their auxiliary devices, the TITAN facility for mass measurements, and the development of laser spectroscopy are crucial to these studies. Studies at TRIUMF-ISAC and ISAC-II will be complemented by experiments at other facilities that possess unique experimental capabilities. EMMA is nearing completion and ARIEL and GRIFFIN are both approved for construction.

Canada has made a significant investment to lead the global effort to understand the origin of the elements. TRIUMF, through the ISAC-I and ISAC-II facilities, is a leading laboratory in the global effort to produce the rare isotope beams required to understand the production of chemical elements in stellar burning and explosive astrophyiscal environments. The Canadian community has focussed on measurements to understand the nature of the resonances in nuclei involved and also direct measurements of key reaction rates in experiments at both ISAC and ISAC-II. The DRAGON and TUDA facilities, complemented by the new TACTIC device—a time projection chamber that employs He gas as an active target—will continue to perform extensive measurements of astrophysically important reactions.

The question of the origin of the heavy elements is universally acknowledged to be one of the most important unsolved problems in science. The present evidence indicates that roughly half of the elements heavier than zinc (A>70) are synthesized in a series of rapid neutron-capture reactions interspersed with photodisintegrations and beta decays known as the r-process. This production mechanism involves highly unstable, neutron-rich nuclei. The pathway along which the r-process proceeds is unknown, but is believed to lie where the neutron separation energy is so low that its neutron capture rate is in equilibrium with the photodisintegration rate of its neutron capture daughter. With neutron-rich beams produced by ISAC's actinide targets, the photofission of uranium at TRIUMF's new ARIEL facility, and the spontaneous fission of ^{252}Cf at the CARIBU facility at Argonne National Lab in the U.S., the Canadian community will be able to make important contributions to the understanding of the r-process through mass measurements with TITAN and the Canadian Penning Trap (CPT). In addition, beta decay lifetime measurements using the 8π and GRIFFIN array, and measurements with the neutron array DEuterated Scintillator Array for Neutron Tagging (DESCANT) of the beta-delayed neutron emission probabilities, which can shift the final abundances in the r-process by one mass unit, will be made.

c. High-Precision Approaches: Testing Fundamental Symmetries

Measurement of Weak Charge and the Running of $\sin^2 \theta_W$

Canadian research in parity-violating scattering experiments is stronger than ever. The MOLLER experiment is one of two experiments highlighted by an international review committee of Jefferson Lab for their discovery potential (the other being GlueX). The measurement will be carried out by rapidly flipping the longitudinal polarization of electrons that have been accelerated to 11 GeV, and observing the resulting fractional difference in the probability of these electrons scattering off atomic electrons in a liquid hydrogen target. The asymmetry is proportional to the weak charge of the electron, which in turn is a function of the electroweak mixing angle, a fundamental parameter of electroweak theory. The accuracy of the proposed measurement will provide a value of the mixing angle with precision on par with the two single best measurements of the same parameter at electron-positron colliders, and will be sensitive to extra gauge bosons, leptoquarks, and signatures of supersymmetry in the one to 10 TeV mass range.

At the low-energy, high-precision frontier, atomic parity violation (APV) provides an independent measurement of the electroweak coupling and its dependence on distance scale. Atomic parity violation is strongly enhanced in heavy atoms, but the atomic structure calculations necessary to extract the weak physics is only feasible in alkali atoms. In francium (Fr), the APV effect is 18 times larger than in cesium. However, Fr has no stable isotopes and must be produced at a radioactive beam facility such as TRIUMF-ISAC. The Francium Parity Non-Conservation (FrPNC) collaboration has been formed to perform fundamental symmetries measurements with cold, trapped Fr at ISAC, and will begin placing equipment on the floor in 2011.

Electric Dipole Moment Measurements

Canadian groups are very active in this field, which has a strong overlap between atomic, nuclear, and particle physics, and are well positioned to be part of breakthrough discoveries. The Canadian-based experiments benefit from the unique capabilities at TRIUMF-ISAC. The atomic EDM measurements (radon, and possibly francium) rely on the actinide target to produce heavy isotopes of choice where the underlying Time/CP-violating interactions are strongly enhanced, and will benefit from the availability of the GRIFFIN array for γ-ray detection. Nuclear structure studies must identify the most suitable Rn isotope for EDM measurement, primarily through beta decay studies with the 8π or GRIFFIN arrays.

CKM Unitarity Tests

Testing the unitarity of the CKM matrix has been an important goal for Canadian subatomic physics. Complementary efforts to study flavour physics at CLEO, the Tevatron, BaBar, and TRIUMF have all contributed to stronger limits on unitarity violations.

The first row of the CKM matrix provides the most demanding test of the unitarity condition, with the sum dominated by the matrix element relevant for nuclear beta decay. Using beta decays of nuclei with neutron number approximately equal to proton number, the decay rate can be used to determine this quantity. The experimental determination of the decay rate involves measurements of the masses of the parent and daughter nuclei, to a precision of a few parts in 10−8, and the half lives and branching ratios to a precision at the 0.05 percent level. A program of such measurements at ISAC has already been highly successful and, once the requisite beams are developed, additional cases from the light mass 10 carbon to the heavier 70 bromine will be studied. With the ability to measure half lives to very-high precision, the new GRIFFIN spectrometer that will have an unprecedented sensitivity for weak β branches, and the TITAN spectrometer for mass measurements, TRIUMF is well positioned to be the world-leader in such measurements.

Beta Neutrino Correlations

TRINAT has pioneered the use of trapped atoms to measure beta decay correlations. Recent approved upgrades will enable TRINAT to pursue a beta-neutrino correlation measurement that presently puts the best model-independent constraints on scalar interactions in the first generation of particles, and a spin-polarized experiment sensitive to a variety of new interactions. In particular, TRINAT will measure one of the decay correlation parameters that are sensitive to sources of time-reversal violation relatively unconstrained by EDM experiments.

Search for CPT Violation

The Antihydrogen Laser PHysics Apparatus (ALPHA) collaboration, of which Canada forms more than a third, seeks to test the CPT theorem that underlies quantum field theories. A comparison of the properties of hydrogen and antihydrogen can potentially provide a stringent test of this symmetry for baryon-lepton systems. The program aims to develop the trap for antihydrogen atoms that will enable precision measurement of atomic transitions and their ground state hyperfine interval. Measurements of these properties in hydrogen are among the most precise in experimental physics. ALPHA has recently succeeded in trapping antihydrogen atoms for over 16 minutes, which is long enough to begin studying their properties in detail. Microwave spectroscopy on the trapped antihydrogen will commence in the 2012-2013 time frame, with the precision measurements beginning in 2014.

The T2K Experiment

The goal of the T2K experiment is to learn more about how neutrinos oscillate. The project was conceived, designed, and constructed in the past decade, and has been collecting data since January 2010. Protons from the J-PARC are used to produce an intense neutrino beam of one type—muon-neutrinos—directed to the large underground SuperKamiokande (SK) detector 295 kilometres away, where the fraction that has changed to other types of neutrinos (electron- or tau-neutrinos) is determined.

Since its inception, Canada has played a major role in the project. Canadians proposed the idea of optimizing the neutrino beam energy by centering it a few degrees away from the SK detector, and have taken the responsibility for the construction and operation of critical detectors that monitor the proton beam and the properties of neutrinos before they have had a chance to oscillate. The image below shows a neutrino interaction in the first of the two dense fine-grained detectors (FGDs). Hundreds of thousands of such events will be recorded so that the properties of the neutrino beam and of neutrino interactions will be well understood in order to make the best possible measurement of neutrino oscillation.

On March 11, 2011, a devastating earthquake and tsunami struck Japan, off the east coast, some 200 kilometres north of J-PARC. The lab was protected from the tsunami, but the earthquake caused some damage to the accelerator infrastructure. The detector components provided by Canada show no sign of damage. Recovery of the accelerator is underway and operations are scheduled to restart at the end of 2011.

d. Underground Approaches: Measuring Neutrino Mixing and Neutrino Properties

Several physics goals are identified in the neutrino sector, all of which are being aggressively pursued by Canadians. The overall scale of neutrino masses and the Majorana or Dirac nature of neutrinos are pursued by the neutrinoless double beta decay experiments SNO+ and EXO. Observation of this process would also demonstrate that lepton number is not a conserved quantity. The T2K experiment will investigate the remaining unknown quantities necessary for a complete description of neutrino mixing.

T2K

Canadians started working on the T2K project in 2000. Beginning in 2006, they received NSERC support to build key sub-components of the near detector (ND280) and critical components associated with beam monitoring; while TRIUMF made significant contributions to both the beamline and detector construction, as well as commissioning. Canadians now play leading roles in physics analysis, including holding the position of physics analysis coordinator for T2K's near detector, conveners of several analysis groups, and the ND280 run coordinator.

T2K recently completed its first year of successful operation, collecting commissioning data from December 2009 to June 2010, and has released its first results. Beam resumed in November 2010, but was interrupted by the March 2011 earthquake.

By 2015, T2K is projected to have accumulated about half of its proposed exposure, giving it a sensitivity factor 10 times greater than existing measurements from nuclear reactors. Two additional years of running at peak beam power will allow T2K to achieve its proposed statistical precision. Over this period, the Canadian efforts will be focussed on operations and maintenance of their detector components, calibration and analysis of data from these detectors, and a wide variety of contributions to higher-level physics analysis. Initial efforts in contributing to analysis of T2K data from Super-K (near detector versus far detector) are already underway.

SNO+ builds on the SNO infrastructure by replacing SNO's heavy water with a liquid scintillator. By transforming SNO into a liquid scintillator detector, a new experiment with diverse physics goals has been created. First, a competitive, next-generation double beta decay experiment can be carried out with neodymium-150 (Nd) loaded in the liquid scintillator. Next, the detection of low-energy solar neutrinos and, in particular, the pep solar neutrinos has the potential to probe the neutrino-matter interaction with sensitivity to new neutrino physics. Finally, the SNO+ detector maintains excellent supernova neutrino capabilities.

SNO+ will start taking data in 2012 and will run in two phases. The first phase will study double beta decay with natural Nd loaded into the liquid scintillator. The second phase will study solar neutrinos starting in 2015. At SNOLAB depth, muon-produced backgrounds that prevent this measurement at other sites are not an issue. These solar neutrinos are particularly interesting to study because their flux can be predicted with a small uncertainty. As a test of the neutrino-matter interaction, SNO+ is the best foreseeable experiment proposed. Between three and five years are necessary to reach the ultimate sensitivity, again depending on the backgrounds.

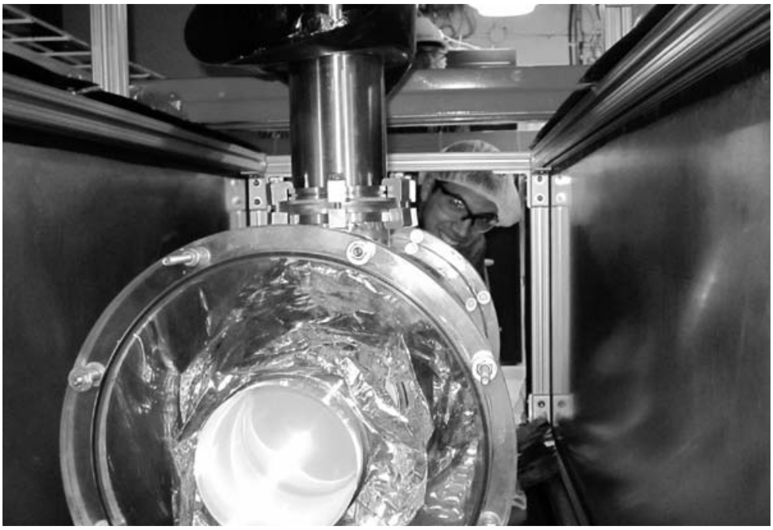
e. Low-Background Experiments: Particle Astrophysics and Direct Detection of Dark Matter

The Canadian subatomic physics community is currently engaged in three complementary direct Dark Matter searches, all eventually to be based at SNOLAB. These experiments—DEAP, PICASSO and SuperCDMS—all seek to detect weakly interacting massive particles (WIMPs) through collisions with nuclei in the detector material. The projects are natural off-shoots of the expertise developed in SNO and the SNOLAB facility is ideal to host them. There are also indirect observation searches with the Very Energetic Radiation Imaging Telescope Array System (VERITAS) or IceCube through gamma-ray or neutrino production from relic particle annihilation, and direct production searches in ATLAS. In this section, we outline the three direct Dark Matter search experiments.

DEAP

The Canadian-led DEAP detector uses liquid argon as a target material in order to probe the spin-independent interactions of WIMPs. It has two phases: DEAP-I—a prototype used to assess background discrimination and to develop low background techniques; and DEAP-3600—the 3.6-tonne physics detector scheduled to be installed in SNOLAB in 2012. The high sensitivity of DEAP-3600 will be achieved from the very large target mass and the very low backgrounds possible in target and detector construction, self-shielding of background radiations and the radio-quiet environment of SNOLAB.

The design for the DEAP-3600 detector is a large spherical acrylic vessel filled with 3.6 tonnes of liquid argon (Ar), viewed by 266 photomultiplier tubes (PMTs) through acrylic light guides. The DEAP-I prototype has demonstrated the ability to sufficiently discriminate between nuclear and electronic recoils in liquid Ar, with future runs of DEAP-3600 expected to use Ar depleted in ^{39}Ar to reduce this background further.



The DEAP-I prototype detector

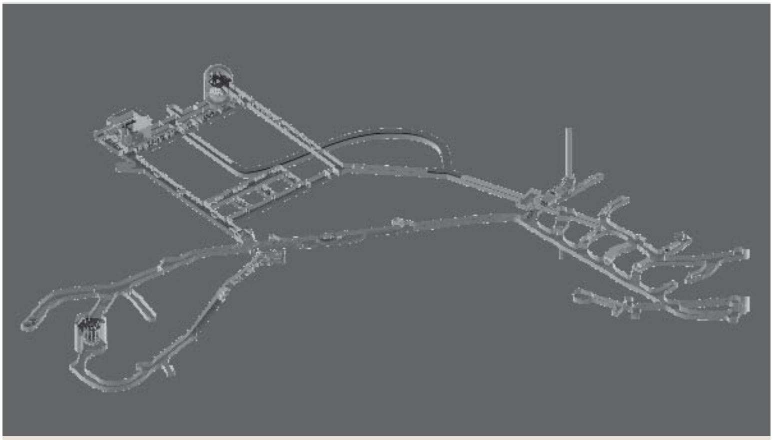
PICASSO

The Canadian-led PICASSO detector is a mature technology focussed on the search for WIMPs through their spin-dependent coupling to target nuclei (in contrast to DEAP's sensitivity to spin-independent couplings), specifically fluorine-19. WIMPs may have stronger spin-dependent interactions, leading to a first observation with these techniques, and the spin dependent and independent cross sections are largely uncorrelated; therefore, limits from both provide a powerful tool for model diagnostics. The detection of an interaction uses the bubble chamber principle, with acoustic readout of the signal. This detector has been operational since 2008, and has recently been relocated to the new Ladder Lab facility within SNOLAB. The 2009 analysis of data collected from the PICASSO array led to a world-best limit on the spin-dependent interaction cross-sections of WIMP particles on nuclei. Improvements in the backgrounds of the PICASSO modules are expected in future runs, with the development of a lower activity matrix for the super-heated droplets.

SuperCDMS

The international CDMS collaboration currently operates an array of low temperature germanium and silicon detectors at the Soudan underground facility in Minnesota. The detectors search for spin-independent elastic recoils of WIMPs off the germanium nuclei by searching for the ionisation and phonon signatures expected with this interaction.

New detector technologies are being explored for the future project, SuperCDMS, which will use larger crystals with a new electrode structure to further improve background rejection, specifically the low energy surface beta interactions. The final objective of SuperCDMS is a detector mass of 150 to 200 kilograms, with this phase to be deployed at the greater depths of SNOLAB to remove potential cosmic-ray muon-induced backgrounds in the larger array.



The SNOLAB Laboratory

The SNOLAB underground laboratory in Vale's Creighton mine has been designed to house the experiments that seek to answer the fundamental questions of particle-astrophysics, and particularly focus on the direct detection of Dark Matter and on measurements of neutrinos.

The underground infrastructure is shown above. The objective is to provide sufficient space so that a number of experiments can be accommodated, with an expected program that supports the project lifecycle of prototyping, construction and operation. The major experimental space consists of the existing SNO cavern and support areas, the new large rectangular hall (Cube Hall) and its support space, the Cryopit cavern, engineered to handle experiments with large volumes of cryogens or noxious gases, and the Ladder labs for medium-sized experiments.

In contrast to other underground laboratories, the entire space is constructed and operated to be a clean room of about class 2000 through high-efficiency particulate air (HEPA) filtering of incoming air and careful management and cleaning of materials and personnel. With this level of cleanliness, it is much easier and more reliable to achieve the low backgrounds in critical spaces required for the next-generation of experiments.

f. Theory

Continued Canadian leadership in subatomic physics also requires that the strength of theoretical subatomic physics in Canada be maintained. Close interactions between theorists and experimentalists are a crucial part of any scientific program, and several theorists in Canada are members of, or collaborate closely with, experimental collaborations like the ATLAS collaboration at CERN, where they provide theoretical insight into approaches to data analysis and possible signals of new physics. More broadly, a vibrant and diverse theoretical community with interests reflecting the most actively pursued questions in the field is necessary for Canadian subatomic theory to participate at the highest level internationally.

But, like the experimental program, subatomic theory is an international enterprise and collaborations between theorists and experimentalists are not restricted just to within Canada. Just as Canadian experimenters profit from collaborations with theorists elsewhere, theorists in Canada interact with a variety subatomic physics experiments around the world, such as the CMS experiment at CERN, dark energy experiments, and others. This diversity allows Canada to benefit from breakthroughs in these other programs in a way that strengthens our own targeted research activities, most notably the flagship research programs.

The past decade has seen significant renewal in the Canadian subatomic theory community, with approximately half of the current subatomic theory faculty in Canada hired over this period. In particular, the Canadian subatomic theory community currently has a significant cohort of young, highly active researchers, many of whom have been attracted to Canada over competing international offers because of the strength and vitality of the Canadian research environment and the internationally competitive level of support available. The research activities in the Canadian theory community fully reflect the challenges posed by the fundamental questions of interest to Canadian subatomic physics, and range from nuclear structure and nuclear astrophysics through particle phenomenology and particle astrophysics to string theory. These scientists are based largely at universities, but TRIUMF and the Perimeter Institute also host significant numbers.

Although theorists may sometimes seem to work alone, most collaborate in small groups on particular problems. These collaborations tend to see results emerge quickly and thus evolve rapidly when compared to most experimental projects. This framework allows individual theorists the autonomy required to move quickly in new and promising directions. At the same time, a strategic move to participate in significant new experimental programs is typically accompanied by the hiring of theorists in related areas. In particle physics, for example, the advent of the LHC was accompanied by a number of theory hires in particle phenomenology, together with significant

Canadian-based efforts to increase the interactions between theorists and experimentalists. Thus, the Canadian subatomic physics community's long-range planning and prioritization process naturally influences the research concentrations of the theory community.

The most significant structural change to the theory landscape in Canada over the past decade has been the growth of the Perimeter Institute (PI) in Waterloo, which now includes world-class groups in quantum gravity, cosmology and string theory (in addition to other targeted fields outside of subatomic physics). Since 2006, the PI has grown significantly. In addition, roughly one-third of all subatomic theory postdoctoral positions in Canada are currently associated with the PI. Subatomic physics is identified as a central scientific priority in the PI's five-year plan and there are plans for further expansion in the area, including the recent launch of a new group in particle phenomenology. As with TRIUMF, the PI is working with the rest of the subatomic physics community to ensure that Canada maintains and enhances its leadership in strategic areas of theoretical subatomic physics.

3. The Longer View: Beyond 2016

We expect significant new results that will reshape our understanding of subatomic physics in the coming five years. LHC experiments may have discovered new physics at the electroweak energy scale, Dark Matter may have been detected, T2K may have observed oscillation from muon to electron neutrinos, and neutrinoless double beta decay may have been observed. Planning beyond 2016 depends on the outcomes of the current set of experiments, though virtually all of the projects listed here are certain to move forward in some form.

a. ARIEL

During the tenure of the current LRP, TRIUMF will build a new electron LINAC, the keystone of the ARIEL project. ARIEL's role is two-fold: it will test acceleration technology and the capability of Canada to build 1.3 GHz RF-cavities for the International Linear Collider; and its electron beams will produce rare isotope beams through photofission of uranium. ARIEL represents a showcase of collaboration between subatomic physics R&D (for the ILC), support for the existing program (this will benefit the TRIUMF-ISAC program in multiple areas) and collaboration with Canadian industry to help them innovate and engage in global projects.

The ARIEL project is planned to ultimately provide 50 MeV electron energy, high- average-current of 10 milliamps. The photofission of uranium will provide an intense source of neutron-rich nuclei for study. These neutron-rich isotopes will be used for an extensive program of nuclear structure and astrophysics. A key aspect of developing this capability is the construction of new target stations, mass separators, and beam transport lines in the period beyond 2016. The ARIEL project will also provide for the construction of a second proton beam line for rare isotope production. These implementations would put ISAC on the trajectory to become the first multi-user radioactive beam facility worldwide with tremendous potential for scientific discovery and advancement in the field.

b. ATLAS Upgrade

The current ATLAS data-taking period is foreseen to continue throughout the period of the next five-year plan. However, there are already upgrade plans for the LHC to increase the design luminosity by another order of magnitude, in stages. In addition to this, several of the detector subsystems will also be reaching their radiation damage limits by about 2014. Upgrades to both the LHC and ATLAS will ultimately be driven by the need to improve the precision of any initial discoveries, such as the Higgs or a dark matter candidate, and/or to extend the reach of the experiment into new domains suggested by the initial results. The Canadian ATLAS group has already been involved in the detector upgrade R&D effort in the areas of very high-rate energy measuring calorimeters, advanced high rate Cherenkov counters and thin, radiation-tolerant pixel radiation detectors. Another option under consideration is to upgrade the energy of the LHC to 28 TeV in proton-proton collision centre of mass. Any such effort will be well beyond the current planning period and Canadian researchers have not yet identified possible roles in this upgrade.

c. EXO

The EXOcollaboration is developing time projection chamber (TPC) technology to search for neutrinoless double beta decay of xenon-136. Canadians have been involved since 2004 in EXO, providing the resources and expertise necessary to build a dedicated prototype for a gaseous configuration of the experiment.

The EXO-200 detector is currently being commissioned at the Waste Isolation Pilot Plant near Carlsbad, New Mexico. EXO-200 will take data for three to five years. Beyond the physics results, EXO-200 will have determined the backgrounds and ease/cost of operating a large liquid detector. At that point, a prototype experiment known as the Xenon Electroluminescence Prototype (XEP) will have answered similar questions for a gas detector. Designs for a liquid and a gas full EXO detector are underway. A decision on the technology choice for the full EXO experiment is expected by 2015.

ISAC

ISAC at TRIUMF uses the proton beam from the main TRIUMF cyclotron to produce rare isotopes via spallation reactions on various targets. Proton beams bombard a variety of targets, from silicon carbide to tantalum, and recently a uranium carbide target has become available for use with up to 10 microamps. The isotopes produced in the target are extracted and ionized. Passing the positively-charged ion beams through a magnetic separator allows the selection of the mass with a resolution better than one part in a thousand—sufficient to separate nuclei with different total numbers of proton and neutrons. These mass-separated beams can then be transported to experimental stations or accelerated to higher energy.

The experimental instruments at ISAC are state-of-the-art, and include devices such as TITAN for mass measurements, the 8π and TIGRESS arrays for γ-ray spectroscopy, the DRAGON and the TRIUMF U.K. Detector Array (TUDA) spectrometers for reaction measurements important for nuclear astrophysics, and the TRINAT facility for precision weak-interaction tests.

All together, ISAC is one of the premier facilities for experiments with rare isotope beams, addressing the leading questions in subatomic physics.

d. ILC

The ILC is a proposal for a new e+ e− linear collider with the stated aim of performing precision studies of the physics revealed by the LHC data. The project design will be completed by the end of 2012 and Canadians have played roles in both the accelerator and detector research and development, as well as theoretical efforts in ILC phenomenology and coordinating roles in the worldwide studies for the physics case.

The design of the ILC calls for super-conducting radio frequency (SRF) cavities and Canadians are developing the expertise to be able to construct such cavities here in Canada working with industry. Through this project, Canadian universities are working to develop graduate programs in accelerator physics to train the next generation of Canadian accelerator experts and are actively recruiting graduate students.

The Canadian ILC detector development effort is focussed around two areas: time projection chambers (TPCs) and calorimetry. Canadian groups have been active in ILC TPC R&D since 1999, and have made significant contributions to the field. This work directly led to the incorporation of TPCs for the near detectors of the T2K experiment for which Canada took responsibility. Since 2005, Canada has been a member of the CAlorimeter for the LInear Collider Experiment (CALICE) collaboration for ILC calorimetry and has been actively involved in analyzing test beam data collected at CERN and Fermilab.

By the end of 2012, the ILC community will complete a cost-to-performance optimization of the accelerator and detector designs. Given suitable physics motivation, this would put the international particle physics community in a strong position to move forward quickly to propose such a large internationally cooperative project. In parallel, R&D on alternative accelerator technologies, such as Compact Linear Collider (CLIC) or a muon collider, with the potential for higher lepton collision energies is being pursued in the event that more than one TeV is needed to precisely measure the new physics uncovered at the LHC.

e. SNOLAB: Neutrinos and Dark Matter

If the current generation of experiments discovers Dark Matter, the focus will become to measure the properties—mass, energy, direction distributions—of those Dark Matter particles. If Dark Matter remains elusive, experimental programs will need to be designed to probe the shrinking regions of parameter space.

The SNO+ experimental program—double beta decay and solar neutrinos—is expected to run well beyond 2016. SNO+ can be greatly enhanced with enriched isotopes or new techniques for increasing the loading of double beta decay candidates into liquid scintillator.

f. SuperB

The study of the flavour structure of the quark sector has been a key area of research for Canadian high energy physics. Although the overall picture is consistent with the Standard Model interpretation, a number of "tensions" are present in the combined fit of these results—potential signs that new physics waits to be discovered. Over the first five years of the planning period, Canadians will still be analyzing the wealth of data produced by BaBar. Simultaneously, the community will be preparing for the next generation of flavour experiment—SuperB.

The SuperB project, which recently received full funding approval from the Italian government, will be sited near Rome, Italy. It is expected to improve the statistical precision of heavy-quark physics measurements by an order of magnitude compared to that of the present experiments. The Canadian group is contributing to the development of a full Technical Design Report for the SuperB project which is expected to be completed by 2012. The Canadian effort focusses on R&D for the large-volume drift chamber which will be the primary tracking system for charged particles. The Canadian group is developing novel techniques for gaseous tracking and particle identification in a high-luminosity environment. Members of the group also contribute to physics studies which will ultimately define the benchmarks for detector performance.

g. T2K

The future of T2K depends to a large extent on the findings from its current run and from other experiments. The search for leptonic CP violation, expressed as a difference between the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ probabilities, would motivate a follow-up measurement. Proposed experiments such as Hyper–Kamiokande in Japan and the Long Baseline Neutrino Experiment (LBNE) experiment in the U.S. would use much larger far detectors and beam power upgrades to search for this matter-antimatter asymmetry. The Canadian T2K group is following these developments closely, and depending upon initial results from T2K could become involved in R&D for a phase-two experiment in the 2013-15 period, with construction of new detectors beginning after 2015.

h. UCN

The Ultra-Cold Neutron (UCN) facility being constructed at TRIUMF will produce the world's most intense source of cold neutrons that can be used for a variety of studies. The first stage, in collaboration with the Research Centre for Nuclear Physics (RCNP), Osaka, will see a neutron EDM experiment mounted at the RCNP with the goal of improving the current limit by a factor of three. During that time, the new beamline will be constructed at TRIUMF with the aim of moving the UCN source from RCNP to TRIUMF in 2014. The UCN facility will be commissioned in 2015, with the undertaking of further neutron EDM experiments the first priority.

In addition to making a new measurement of the EDM of the neutron, a host of other physics experiments are also envisioned at the UCN source at TRIUMF. For example, one can probe short-distance gravity from neutron quantum states in a gravity well, or neutron-antineutron oscillations. The project is presently a collaborative effort between researchers in Japan, Canada, and the U.S. The group is currently investigating and prototyping the experimental system with activities in Japan and Canada.

i. Summary: The Canadian Program

International science is, by its very nature, both cooperative and competitive. Cooperation, planning and strategic decision-making within Canada have built a strong program that positions us well internationally. Our past scientific accomplishments have gained us the respect of the worldwide subatomic physics community.

Strategic investments in both domestic and international facilities over the past 10 years have brought us to the brink of discovery in several areas of subatomic physics. We are now prepared to reap the scientific rewards for these investments. As we move forward, the Canadian subatomic physics community will continue its tradition of evaluating the physics benefits of emerging projects and making careful choices that build on our past successes.

5

Broader Impacts on Society

Canada has traditionally played a strong role in the international subatomic physics research community. In this quest to push the frontiers of human knowledge, new tools are developed, new global partnerships are built, new markets are created, and a new generation of innovators is trained with a unique skill set. Canada's leadership position in subatomic physics has created these favourable societal impacts and impressive returns on investments. There are several excellent examples of Canadian success stories that will be illustrated in this section of the LRP document. There is the potential to further exploit both the scientific and economic opportunities that will arise in the coming years. To do so, it is vital that investment in subatomic physics research grow and that the ties to industry be strengthened.

1. The Technological Impact of Subatomic Physics

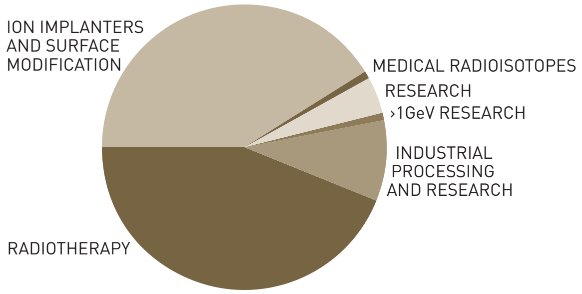
Subatomic physics research rarely relies on technologies that are simply "off the shelf." Technological innovation is a prerequisite for discovery in this field, and these innovations often occur through partnerships between subatomic physicists and industry. Technologies developed as part of subatomic physics research have changed the world we live in.

- **Human Health—Cancer Therapy:** Radiation therapy, using radioactive materials placed inside the body (brachytherapy) or particle beams (external beam therapy), was developed from subatomic physics research. There are about 10,000 accelerators worldwide presently devoted to radiation therapy, with millions of successful treatments. Due to Canada's strong background in experimental nuclear physics, many of the radiation physics techniques used worldwide in this therapy were also developed in Canada.

- **Human Health—Magnetic Resonance Imaging (MRI):** The principles behind MRI were established more than 60 years ago through the understanding of the influence of strong magnetic fields on the atomic nucleus. However, this did not mean that a practical MRI machine could be built, since the magnetic fields required to obtain a useful image are huge. The problem was eventually solved when superconducting wire capable of handling a high operating current was developed for particle accelerators. Oxford Instruments, located not far from the subatomic physics laboratory that succeeded in this development, asked the researchers to develop the first powerful magnets for MRI scanners, which have become standard diagnostic equipment for large hospitals across the world.
- **Human Health—Particle Accelerators for Nuclear Medicine:** Particle accelerator technology originally developed for subatomic physics research currently supplies about 10 percent of the world supply of medical isotopes. In Vancouver, Nordion Inc. operates three medical cyclotrons for the production of isotopes—such as Sr/Rb-82, I-123, Tl-201—which are exported worldwide. This work is a direct spin-off of Canada's investments in the TRIUMF subatomic physics laboratory.
- **Security:** Subatomic physics techniques are now used in Radioactive Threat Detection technology to detect neutrons (nuclear waste materials) and gamma rays (dirty bombs) during routine x-ray inspections of cargo and at border crossings. Subatomic physics techniques are also used to detect land mines and improvised explosive devices.
- **Information Technology:** Subatomic physics research is computation- and network-intensive. To meet their goals, subatomic physics researchers have been at the forefront of innovation in this field, with significant contributions to grid computing, data mining, and cloud storage. An often-cited historic example is the invention of the World Wide Web at CERN to solve some of the information sharing challenges created by worldwide subatomic physics collaborations.
- **Manufacturing—Industrial Electron Beams:** The market for industrial electron beams now totals $50 billion per year. For example, most of the cereal boxes in the grocery store aisle are printed using electron-beam-cured inks and coatings. Their fast drying times allow for faster web-press printing.
- **Materials Science—Synchrotron Radiation Facilities:** First observed in early particle accelerators, the intense x-ray beams produced at synchrotron radiation facilities provide a powerful probe for material/biological sciences and technologies. Such facilities are often developed from, or interlinked with, nuclear and particle physics accelerator facilities.
- **Digital Electronics:** Thousands of accelerators are at work every day producing particle beams in manufacturing plants and industrial laboratories. For example, all digital electronics now depend on particle beams for ion implantation, creating a $1.5 billion annual market for ion-beam accelerators. All the products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500 billion.

The Role of Accelerators

The use of accelerators is a common feature in many spin-off technologies from subatomic physics research. The chart below shows the breakdown of the approximately 26,000 accelerators in the world today. Eighty-five percent of the total are used for ion implanters or radio therapy, while only a small fraction are used in pure research applications.



2. Technological Impacts—Canadian Successes

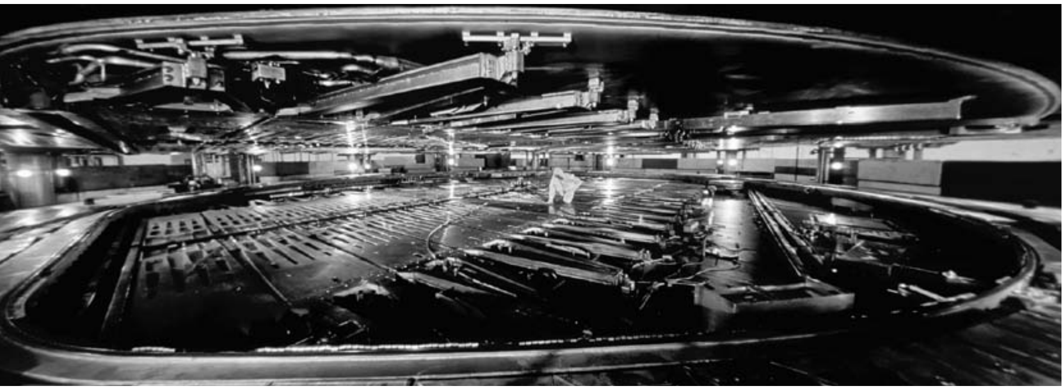
There are many stories of Canadian subatomic physicists who have brought technological innovation to the private sector. Below we have chosen a few select examples from human health, security and information science.

Human Health: Positron Emission Tomography

TRIUMF's Thomas J. Ruth is the recipient of the 2011 Michael J. Welch Award, in recognition of his contributions to the development of Positron Emission Tomography (PET)—a technique to image tumours and to study brain and heart function through the use of short-lived isotopes produced at a nearby accelerator. During his career, he oversaw the installation of four PET scanners and the TR13 cyclotron, which is specially designed for producing medical isotopes. The TR13 became the prototype for the low-energy TR series of cyclotrons manufactured by ACSI in Richmond. He has also been working with researchers at the BC Cancer Agency, Lawson Health Research Institute in London, Ontario and the Centre for Probe Development and Commercialization in Hamilton, Ontario on the proposal to develop the production of technetium-99m (Tc-99m) via PET cyclotrons to help ease the shortage of this isotope.

Human Health: Time of Flight Mass Spectrometry

University of Manitoba physics professor Kenneth Standing started his career as a nuclear physicist. Time-of-flight mass spectrometry has existed since the 1940s but it was in the 1970s—with better computers and electronics, and a new kind of ion source—that it became practical for biological applications. That's when Standing shifted his focus to mass spectrometry.



Inside TRIUMF's 500 MeV H^- cyclotron, the world's largest cyclotron.

Advances in ion sources and mass spectrometers from Standing's group have allowed for the analysis of increasingly larger biological molecules, like proteins. As a result, mass spectrometry is now a pivotal tool in the new field of proteomics—the attempt to identify the structure and abundance of all of the proteins in an organism, just as genomics seeks to identify all of the genes.

In 2003, members of the Standing/Ens research team helped identify and characterize key proteins of the SARS virus using mass spectrometry techniques, weeks before its genome was fully sequenced. The research group has participated in projects that evaluate cancer treatments, study tissue transplant rejection and aim to understand disease resistance in wheat. Recently, it has participated in a project that is developing improved methods of biofuel production.

Security: Detection of Land Mines

Hidden or obscured bulk explosives threats—such as unexploded ordnance (UXO), landmines and improvised explosive devices (IEDs)—are a major concern to the armed forces and public security agencies of many countries. After receiving his PhD in nuclear physics from McMaster University in 1978, John Elton McFee of Defence R&D Canada has been conducting research in the detection of mines, minefields, unexploded ordnance and improvised explosive devices for over 30 years, and is internationally recognized as being among the leading researchers in the field. For the last 16 years, he has researched nuclear methods of detecting bulk explosives. In close collaboration with a few key Canadian companies, methods suitable for vehicle-mounted or fixed-position applications and those suitable for person- or small robot-portable roles, have been studied. Vehicle-mounted systems mainly employ detection of characteristic radiation, whereas person-portable systems use imaging of back-scattered radiation. Dr. McFee shared the 2000 Canadian Nuclear Society Hewitt Award for developing the first fielded thermal neutron analysis (TNA) mine detector and his devices are in use by Canadian forces personnel in the field.

Information Technology: Data Mining

After completing his PhD in particle astrophysics at McGill University, Claude G. Theoret became the founder and President of Nexalogy Environics. The company employs advanced semantic data-mining techniques originating in subatomic physics to quickly and accurately process the large amount of data available in the social media landscape. This analysis is based on co-word analysis and actor-network theory, which is used to identify and interpret vital networks communicating on-line. Dr. Theoret is responsible for the development of the advanced analysis tools at Nexalogy Environics and manages all quantitative analytics.

Examples of the industrial spin off companies that subatomic physics has already provided to Canada include:

Advanced Applied Physics Solutions Inc. (AAPS)
With support from the federal Networks of Centres of Excellence program, TRIUMF created AAPS in 2008. AAPS operates at arms length from TRIUMF and is one of the only Centres of Excellence for Commercialization and Research (CECRs) in Canada that focusses on commercializing physics and technology arising from subatomic physics research, including:

- muon geotomography: underground detection and analysis of cosmic-ray muons are used to identity and map underground ore bodies;
- high-efficiency electromagnetic separation of isotopes: technologies related to ion sources and high-resolution mass spectrometry are used to dramatically increase the efficiency and yield of stable radioactive isotopes and augment production techniques that are typically limited by low-specific activity; and
- detection of concealed special nuclear material: applied subatomic physics technology is used to develop this capability in conjunction with Carleton University, the Department of National Defence and the Canadian Forces.

A group of technicians from Alston Canada (Lévis, Quebec) with one of the quadrapoles designed at TRIUMF and built in Canada by Alstrom for the LHC at CERN.

Advanced Cyclotron Systems Inc. (ACSI)
In December 2010, TRIUMF and ACSI announced a new partnership agreement with the intention of putting TRIUMF's intellectual expertise in medical cyclotrons and beam targets behind ACSI's world-class product line. In 2010, ACSI sold nearly a dozen cyclotrons around the world, capturing a large fraction of the global cyclotron market.

D-Pace Inc.
D-Pace provides ion-source, accelerator and beam-line technologies and design services to the applied particle accelerator industry, such as the semi-conductor industry for ion implantation, and international nuclear energy institutes. D-Pace and TRIUMF have co-operated closely for many years, especially after December 2001, when D-Pace licensed a group of cyclotron component technologies from TRIUMF. The company has since generated sales in Europe and Asia from the ion-source technology it licensed from TRIUMF. With continuing encouragement and support from TRIUMF, D-Pace has doubled its revenues in each of the past four years and now has customers from France, Japan, South Korea, Taiwan, the Netherlands, and the U.S.. On September 17, 2009, D-Pace was recognized as a Canadian Innovation Leader by the Government of Canada, in acknowledgement of its role in researching, developing, supplying, and commercializing products and services for the international commercial accelerator industry, linking scientific research to commercialization, jobs and economic growth.

Nordion Inc.
Nordion is a transnational health and life sciences company that specializes in radioisotope production and radiation-related technologies used to diagnose, prevent and treat disease. It supplies over two-thirds of the world's medical isotopes used for diagnosing heart disease, brain disorders and infections. Its Vancouver facility, located at the TRIUMF site, provides more than 15 percent of Canada's medical isotope exports, including Palladium-103 used in prostate brachytherapy. This product is based on medical isotope production knowledge licensed from TRIUMF. In addition, a low-energy proton beam from the main TRIUMF cyclotron is used to produce heart-imaging isotopes. A 1995 report by the U.S. Institute of Medicines Committee on Biomedical Isotopes cited the TRIUMF-Nordion relationship as a model of public-private partnership, one that could be emulated in the U.S. In 2004, TRIUMF and Nordion received the NSERC 2004 Synergy Award for Innovation. Since that time, Nordion and TRIUMF have successfully launched several joint ventures—one is a multi-million dollar radiotracer laboratory at TRIUMF where scientists from both laboratories will work side by side, while the other is an NSERC Collaborative Research and Development project with the University of British Columbia. One patent has already been filed for a promising new radiopharmaceutical product.

PAVAC Industries Inc.
PAVAC is a world leader in developing commercial high-energy electron beam applications, most notably the PAVAC LASTRON beam for electron-beam welding. Building on this expertise, TRIUMF and PAVAC have joined forces to fabricate, assemble and test superconducting radio frequency accelerator cavities. These superconducting devices are assembled into modules to form next-generation accelerators with applications in health care, environmental mitigation and remediation, advanced materials science and high-energy physics. This success registers Canada as one of only five countries in the world with this coveted capability, and it allows PAVAC to bid on and supply such devices internationally. Since this milestone, PAVAC has been invited to bid on contracts in the U.S. and, through introductions TRIUMF made in India, has sold two of its million-dollar welding units to India.

3. A Skilled and Talented Workforce

"Talented, skilled, creative people are the most critical element of a successful national economy over the long term."

- *Mobilizing Science and Technology to Canada's Advantage* –2007

The Canadian economy increasingly relies on a highly skilled workforce which is capable of adapting to a rapidly changing technological environment. Further, this new workforce needs to be comfortable working in national and international collaborations. According to the *Statistics Canada 2009 Innovation Analysis Bulletin*, the probability of a firm being innovative is highly correlated with the skill structure of its employees, with innovative firms being more likely to hire people with advanced degrees in science. The high salaries and the very low unemployment rate enjoyed by those holding physics degrees indicate the high value that businesses attach to the skills brought by physics graduates.

In particular, subatomic physics graduate students are trained to use and develop innovative technologies, are accustomed to working in international collaborations, and are forced to innovate in order to produce world-class research results in a highly competitive environment. Graduates with advanced degrees in subatomic physics who have moved to "non-traditional careers" have distinguished themselves with their unique skill sets that contribute significantly to their personal and employer's success. Commonly listed skills learned in subatomic physics that are helpful in subsequent careers include:

- creative problem-solving skills—being able to look at problems from multiple viewpoints and from a different perspective than their peers. This creativity is typically combined with sophisticated mathematical skills, allowing detailed quantitative analysis;
- a deadline-driven and multi-tasking operational environment. In subatomic physics experiments, 24/7 operation and strict deadlines are the norm;

- an international team-oriented working environment including a wide variety of languages, and cultures. The opportunity to interact with and learn from the best scientists in the world;
- hardware skills with novel materials, high-speed electronics, accelerators, etc.;
- complex software design and implementation; and
- quantitative statistical analysis.

Below are several examples from companies that have found these skills to be useful.

Skill Set: Data Mining

A growing area of interest and concern in the private sector is the exponential growth of data used to manage a business; with business intelligence an ever-expanding area of specialization and focus. I have found the skills I developed in subatomic physics—managing and analyzing large volumes of data—indispensable in positioning me as an expert in this area. Beyond reporting, businesses are increasingly requiring analysts to sift through large volumes of data, provide trending analysis, and put forward comprehensive "what-if" scenarios and insight into their businesses. Modelling skills and understanding results from data analysis are all subatomic physics skills that have a direct impact on businesses today. As a senior manager and executive in a number of information technology (IT) organizations since leaving academia, I have hired a number of individuals with subatomic physics background (up to the PhD level) in the capacity of project managers and technical consultants. These individuals have generally stood out from the crowd when it comes to work ethic, ability to have insight into problems and solve them quickly, and design sophisticated solutions for business. Most, if not all, of these individuals have moved on to more senior leadership positions within their respective fields of expertise and organizations.
John Mayer, PhD
Vice-President Enterprise Solutions, Indigo Books & Music Inc.

Data centre for Fermilab collider experiments

Skill Set: Collaborative Skills

The broad scope of high-energy physics has been an excellent preparation for my career in the private sector. By "broad scope" I mean a wide range of aspects, including non-academic ones. For instance, having to find one's way around in a broad collaboration, without guidance about whom to ask for advice or (initially at least) without a clearly-defined scope , is not unlike starting to work for a large bank and getting to know the systems and processes.

I am currently in a managerial position and I have hired a number of people in recent years. However, while I keep a close eye on résumés that list a physics degree, I find these to be exceedingly rare. Perhaps the message that a degree in physics is an excellent starting point for a career in finance needs to be communicated more clearly to graduate students. Similarly, among my peers, I often encounter the tendency to hire somebody specifically for the task at hand, without seeing the potential in a person as a potential long-term employee. I am actively working to dispel this mindset, with limited success. Improving this situation should be on the list of long-term goals of everybody in academia and in the private sector.

Bjoern Hinrichsen, PhD
Large-Scale Computing, CIBC

Skill Set: Creative Problem Solving

Having been trained with the techniques used in the field of subatomic physics, I gained a much better grasp of the fundamental relationship that exists between experimental measurements and their statistical nature. This allows me to exercise a critical and informed judgment on the quality of the data that I receive and how it should be used in analyses—what can be generalized, what can safely be discarded, how different ways of making the measurements or sampling the data can be suggested, how conservative limits can be deduced, etc.

The training in subatomic physics also made me proficient in numerical programming and provided me with a computing toolset that makes me resourceful among my colleagues for finding solutions to experimental data-handling problems.

The analytical skills that were developed in the context of physics studies also represent a great asset in that they provide a means for finding approximations to difficult problems. They also give a sense of what is of greater importance in a formula and how it can be adapted to particular situations that require optimization for lengthy computations. These qualities are the reasons why my employer hires many physics PhD graduates for his team and proudly advertises our great competence to our customers.

Luis Valcarcel, PhD
Research Scientist, SES Technologies

4. Canadian Graduate Survey

In the preparation of this document, we solicited testimonials from past graduates of subatomic physics in "non-traditional" careers. The overwhelming response to our request indicates that these graduates have found careers broadly distributed through the Canadian economy, including:

- Business entrepreneur (software and engineering companies);
- Electronics and engineering;
- Finance (quantitative analyst, financial risk management);
- Geophysics
- Government (radiation standards, radioactive threats, defence);
- Medical imaging;
- Nuclear power (reactor design); and
- Software (web applications, data mining, programmer).

Career Profile: Entrepreneur
Moe Kermani—CHAOS Experiment,
University of British Columbia, 1997
Now—Vice President, NetApp

Moe Kermani obtained his PhD from the University of British Columbia in 1997 for his work on the CHAOS pion scattering experiment at TRIUMF. He has subsequently had a very successful career as a high-tech entrepreneur: first with local Vancouver start-up Sonigistix as their R&D Director; then as co-founder and CEO of Bycast—a leading provider of storage virtualization software for large-scale digital archives and cloud storage. In 2010 , Bycast was acquired by NetApp, where Dr. Kermani is now Vice-President. Dr. Kermani has extensive experience working with entrepreneurial companies and taking leading-edge technology solutions to market. He currently serves on the board of directors of the British Columbia Technology Industry Association and is a winner of the *Business in Vancouver* Forty-under-40.

Students working on the barrel calorimeter for the GlueX detector

Career Profile: Financial Analyst
J. Wendland—HERMES Experiment, Simon Fraser, 2003
Now—Quantitative Research Manager, FINCAD

Jeurgen Wendland came to Canada to obtain his MSc and PhD (2003) in particle physics at Simon Fraser University. There, he worked on the HERMES experiment. After graduation, he received a postdoctoral fellowship at the University of British Columbia to work on SNO and T2K. He is currently with FINCAD—a Canadian financial software company located in Surrey, British Columbia, where he leads a team of quantitative analysts in R&D. The software and numerical analysis skills that he acquired doing analysis of particle physics data were directly applicable to problems in finance, such as, minimization algorithms and Monte Carlo simulation methods.

Career Profile: Financial Analyst
Yashar Aghababaie—Particle Theory, McGill University, 2005
Now—Managing Director, Goldman Sachs

Yashar Aghababaie is Managing Director at Goldman Sachs Investment Banking, which he joined after completing his PhD in theoretical particle physics at McGill University and a postdoctoral position at the University of Toronto. Before his recent promotion to Managing Director, Yashar was Vice-President at Goldman Sachs, with responsibilities in quantitative, algorithmic volatility trading and high frequency options market making. This is the organization within Goldman Sachs that specializes in using very fast computer-driven trading to profit from price spreads.

Career Profile: Security
Anthony Faust—OPAL Experiment, University of Alberta, 1999
Now—Head of Explosives Detection Group, Defence R&D Canada

Anthony A. Faust is Head of the Explosives Detection Group at Defence R&D Canada. Dr. Faust received a PhD in Physics from the University of Alberta in 1999, as part of the Higgs search team for the OPAL experiment at CERN. Upon making the jump to federal science, he found that his subatomic physics background was directly relevant to his new principal research area—the development of active neutron and photon interrogation techniques for the detection of explosive hazards like land mines and improvised explosive devices.

A subatomic physics graduate student working on the 8pi Gamma-Ray Spectrometer at TRIUMF's ISAC facility..

We also received 25 testimonials from graduates about the relevance of their education to their current careers. Space restrictions prevent us from listing all of the testimonials received. An edited selection of them appears below. Please consult subatomicphysics.ca for the full list.

Testimonial: Data Retrieval Entrepreneur

Since completing my studies in high energy physics, I have co-founded Delphes Technologies International—a software company in the area of information retrieval and extraction based on a highly complex treatment of natural languages. I realized rapidly that combining natural languages with computer science reveals high complexity problems similar to those encountered during my work in subatomic physics. The experience I have gained during my research in high-energy physics has, without a doubt, provided me with the ability to face those challenges and to find original and innovative solutions to building highly efficient natural language information management and retrieval software. The software we developed has been used by large corporations and governments. For example, the solution has been deployed as the information retrieval engine for all Government of Quebec departments and organizations. We also raised more than $8 million from international investors creating more than 65 jobs for highly qualified engineers, researchers and scientists. This experience led to my position as Vice-President, Research and Development, at Alphinat Inc.—a Montréal-based public software company providing innovative solutions for rapid web development. I am also acting as consulting expert in the software development area through my own consulting firm—Timeless Technologies International.
Denis Michaud, PhD
Vice-President, Research and Development, Alphinat Inc.

Testimonial: Engineering Entrepreneur

As an entrepreneur and leader, I believe my training as a physicist uniquely prepared me for the world of business. Through my education in experimental subatomic physics I was given a life-changing opportunity to work as part of a group of world-class physicists, engineers and technologists. In this world, where new ideas were encouraged and decisions made not on seniority but by applying logical principles, it was possible for a PhD student in his 20s to influence the design, construction and eventual outcome of a multi-million dollar physics experiment. I believe that my success in business—12 full-time employees and $2 million in sales in 2010—can in large part be attributed to this experience as well as the ab-initio approach to problem solving I learned in subatomic research.

Matthew Smith, PhD
General Manager, SKC Siu Engineering Ltd.; and President, MxV Engineering Inc.

Testimonial: Finance

As a discipline, subatomic physics is perhaps one of the most useful groundings in basic logic and problem solving that one can have. I have travelled a somewhat unconventional route since graduation, and have found myself working in the financial services industry in Toronto. Physicists tend to learn to evaluate problems using extremes, asking questions like, "What would happen if ALL of this demand were to suddenly move this way, would that be a problem?", and learn not to shrink from making estimates where justifiable and doing the math where required. In my business, and in much of society, this is no longer true—if it can't be looked up on the Internet, then it is an insurmountable problem. Where some of my analyst peers are forced to rely on the pronouncements of companies on topics with technical themes, I am free to bring a lot more experience to bear in asking the right questions of management. I have become regarded as the analyst on Bay Street that investors, who have been approached with a technology opportunity that seems too good to be true, should call. I am fairly unique in that regard, and to a large measure that is due to my physics training and research background. I would certainly hire more of this sort of person, if I could find them.

Jon Hykawy, PhD
Head of Global Research, Clean Technologies and Materials Analyst, Byron Capital Markets

Testimonial: Finance

My theoretical particle physics education has provided me with skills that are indispensable in my career as a financial risk manager. The past few years have proved to be one of the most interesting and challenging times for capital markets. My training in physics helped me to develop the ability to question what we believe to be true and why we believe it. This strength has helped me to adapt quickly in a changing environment by dispensing with ideas that no longer function, and adopting and learning new ideas that may be more promising. The process of earning a doctoral degree also helped me to develop confidence to question the "status quo" and to share the new ideas with others. This ability to challenge current beliefs, analyze complex situations in a rigorous way, and to communicate clearly and effectively, are all examples of skills that were encouraged during my particle physics training.

Alexander Marini, PhD
Senior Manager, Market Risk and Risk Technology, La Banque Nationale du Canada

Testimonial: Information Technology

I am currently working in the field of IT, for a company that is a technology solution provider to large enterprises in Canada and abroad. Part of my work involves evaluating new technologies and coming up with innovative ways of using these technologies to solve real business problems. In some ways, this is not very different from certain aspects of my work in experimental particle physics. During my graduate program at the University of Toronto in experimental particle physics, I was heavily involved in many aspects of building an extremely complex environment—from designing and building the detector components, to building the computing systems required to run and operate the detectors and analyze the data. The particle accelerators and detectors are some of the most complex machines in existence today and present us with many technical challenges that often jointly drive innovation in the technology industry. This type of involvement has provided me with real-world skills that can be applied to most business environments. In addition, the skills acquired while working on the physics analysis within an international collaboration of hundreds of physicists are also very applicable to many roles in corporate environments. Being able to articulate your findings or solutions clearly, both in writing and in-person, is also something that one has to learn while collaborating in the subatomic physics community.

Milos Brkic, PhD
Director, Datacenter Technologies, OnX Enterprise Solutions

Testimonial: Nuclear Industry

I was trained as an experimental nuclear physicist. There are very few people left who call themselves nuclear physicists and there is a clear need in a resurging industry. There is a huge need for people in the nuclear industry to supply disciplines peripheral to nuclear and subatomic physics—radiation protection, health physics, nuclear engineering, reactor physics, nuclear medicine, radiation industries (e.g., radiography, contract sterilization)—all requiring these basics skills. Note that I work in a company that heavily services the nuclear industry but has a large number of clients in healthcare, agriculture and other energy industries. Subatomic and nuclear physics are disciplines that are very basic and very innovative, so graduate students have to necessarily be very creative and innovative on their own terms but also learn to get support from like-minded independent individuals wherever they can. I think this understanding makes for adaptability and independence that is not disruptive to team functioning. That's what I think has distinguished me from my peers. I learned early to start-out with some brief calculations on the back of an envelope and build on the results.
John Barnard, PhD
Director, Research and Technology, Acsion Industries Incorporated

Testimonial: Nuclear Security

I am a research scientist in applied subatomic physics with Natural Resources Canada. As an experimental subatomic physicist, I apply my education and do many of the same things that any subatomic physics researcher does. I develop techniques and design detectors for localization and characterization of radioactive threat material. I am leading a multi-institute research team of particle physicists in the design and construction of a gamma imager with state-of-the-art scintillation light collection, as well as multi-channel pulse digitization, synchronization and triggering. We use Monte Carlo simulation to understand the performance of various detector designs. We validate our simulations with careful laboratory experiments. The only difference is that rather than testing the fundamental nature of our physical reality, I am working toward keeping people safe and secure.
Laurel E. Sinclair, PhD
Research Scientist, Natural Resources Canada

Testimonial: Electrical Engineering

Through my training in experimental subatomic physics I have developed lasting skills that have played a key role in the success of my early engineering career. The critical thinking required to resolve challenging technical issues in the subatomic physics field has been directly transferable to the development of novel engineering concepts and designs. I cannot imagine another field where the limits of what is possible are so routinely redefined by those involved. The application of this physics mindset in an industrial design setting is the perfect recipe for innovation.
Joey Gallant, MSc
Engineer-in-Training, Corrpro Canada

5. Demographic Trends and Funding Pressures

Compelling scientific questions and accomplishments have made subatomic physics a leading and growing field of research. The opportunities afforded by new techniques and facilities have created interfaces with other fields (e.g., astronomers collaborating with nuclear astrophysicists to better understand core-collapse supernovae, atomic physicists contributing their expertise to antimatter trapping, radiochemists contributing to ultra-clean underground experiments). As a result of these vibrant and exciting challenges, the number of subatomic physicists in Canada continues to grow, with an average of six new faculty hires per year in each of the last five years. This has led to great scientific opportunities, and stresses, in the Canadian subatomic physics community.

Subatomic physics is an exciting field that continues to attract some of the best and brightest young minds in Canada. To better understand the demographic trends, the committee mined the highly-qualified personnel information in the NSERC Personal Data Forms (Forms 100), submitted as part of the Discovery Grants application process. This information is summarized in Figure 6. The number of students enrolled in subatomic physics PhD programs at Canadian universities has been relatively stable at about 350 per year. There has been a decline in the number of experimental MSc students since 2004, which is likely due to two factors: when experiments transition from installation/calibration to data-taking, the emphasis shifts to supervising PhD students over MSc students, as they are capable and will benefit more from the more-involved physics analysis; and universities, in general, are encouraging strong students to move quickly into PhD programs from MSc programs, mirroring what has been a long-standing practice in the

U.S. The make-up of the postdoctoral fellows (PDFs) research pool has also evolved, with the number of theory PDFs trending steadily upward (from 110 in 2002, to about 150 in 2008), reflecting the increased research capacity and productivity in theory supported as part of the 2002 Reallocations Exercise. After 2007, there are more theory PDFs than experimental PDFs working with Canadian subatomic physics researchers, with about 1.3 theory PDFs per theory PhD student, on average, nationwide.

The challenging operating grant situation for experimental subatomic physicists is a likely explanation for several of the observed trends. In contrast to the situation for theorists, there are only 0.6 experiment PDFs per experiment PhD student. It appears there has been a shift within several experimental collaborations to PhD students instead of PDFs, due to constrained operating grant funding and the concurrent need to have a critical mass on the ground in foreign laboratories. As we have demonstrated above, young subatomic physicists have a high degree of competence in disciplines with applicability far beyond subatomic physics. As a group, they are energetic, hard-working, and highly motivated. They are a valuable national resource, and it is important to optimize and make the most of the benefits—scientific, societal and economic—that their talents bring. Consequently, the continued inflationary erosion of NSERC's subatomic physics envelope, and the long-term implications this will have for the number of young people able to enter the field, is of great concern.

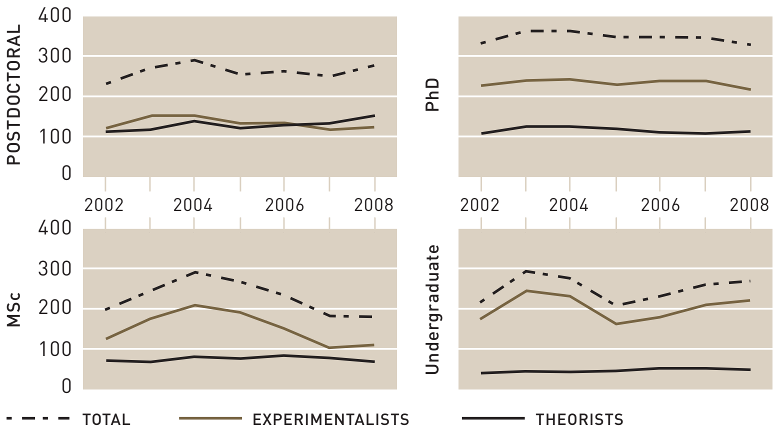


Figure 6: The number of postdoctoral fellows, PhD students, MSc students and undergraduates undertaking subatomic physics research in Canada for the years 2002-08. Experimentalists are shown in brown, theorists in black, and the total in a dotted line. The years shown represent those for which complete data is available, accounting for grant renewal cycles.

6. Strengthening the Ties

While we see positive impacts of subatomic physics research on Canadian society, steps should be taken to further strengthen the ties between basic research and economic benefit. In particular, certain opportunities will present themselves in the next five years and should not be missed. Opportunities exist both in increased direct industrial activity and in the training of a skilled workforce.

a. Opportunity: Joining CERN

“For Canada to prosper in the global knowledge economy, we must excel at connecting to the global supply of ideas, talent and technology. ”
- *Mobilizing Science and Technology to Canada’s Advantage* –2007

CERN is one of the world’s largest and most respected centres for scientific research. Canada has been involved in research at CERN for decades and a significant fraction of our subatomic physics research community relies on their facilities. However, Canada has no formal relationship with CERN. In the past, we have negotiated participation in CERN experiments on a project-by-project basis. As such, we have no influence on the future priorities of the laboratory and Canadian companies do not have access to CERN contracts.

CERN has recently decided to establish a new “Associate Membership” for non-European countries. Canada would be a natural candidate for such a membership, and benefits include:

- Canadian companies bing permitted to bid on CERN contracts and being awarded these contracts in proportion to Canada’s contribution. Approximately one-third of CERN’s budget goes to procurement;
- Canadian citizens having access to CERN education and training programs and limited-term staff positions; and
- Canada having a voice in the scientific and financial decision-making of the laboratory.

The benefits to industry from association with CERN are clear. A study of technology transfer in 629 companies with CERN contracts revealed:[1]

- 38 percent had developed new products;
- 42 percent increased international exposure;
- 44 percent improved technological learning ;
- 17 percent opened a new market;
- 60 percent acquired new customers;
- 52 percent attributed improved sales performance to their relationship with CERN; and
- all firms derived great value from using CERN as a marketing reference.

[1] Technology transfer and technological training through CERN’s procurement activity; E. Autio, M. Bianchi-Streit, Ari-Pekka Hameri (CERN, 2003)

Superconducting accelerator structures made of niobium, developed for research towards a future linear collider.

The benefits from the scientific training perspective are also clear. CERN is not only an elite facility for subatomic physicists to receive training and employment, it is also an elite training facility for other disciplines. The majority of CERN fellows work in engineering, computing or applied physics.

Member states pay for the operation of CERN in proportion to their GDPs. Associate Members would pay 10 percent of the Full Member cost. In this scenario, the value of direct contracts to Canadian industry would be expected to increase from approximately $30,000 in 2010 to more than $3 million per year. The total financial value returned through industrial contracts and training would amount to nearly two-thirds of the Canadian contribution to CERN.

Formalizing our relationship with CERN would therefore strengthen Canadian ties with Europe politically, as well as economically, through strengthened ties to Canadian industry. It would provide unique training opportunities for young Canadian scientists and engineers.

b. Opportunity: Training of Accelerator Physicists

Accelerators are big business throughout the world. New developments in particle accelerator technologies play a crucial role not just in subatomic physics, but also in condensed matter physics, health research, medical diagnosis and treatment, and industry. This is illustrated in the success stories described in previous sections.

There is a shortage of highly qualified graduates with advanced degrees in accelerator science. TRIUMF, in co-operation with several universities, has begun an initiative aimed at addressing this shortage in order to fuel growth in research and business in Canada. We support the continued development of accelerator highly qualified personnel (HQP) training programs in Canada, and encourage NSERC and other relevant bodies to ensure an appropriate mechanism to evaluate the funding requests for these programs.

6

Positioning for Scientific Leadership

Given the nature of experiments needed to continue progress in the field, frontier subatomic physics research requires long-term commitments from governments, laboratories, and physicists. Laboratories that mount the experiments employ hundreds or thousands of staff. Large collaborative teams are necessary to build and operate the experimental apparatus. In order to have the expertise necessary to mount a successful experiment, teams tend to be composed of scientists from around the world. The construction and data-taking phases of the experiments can each take 10 years or more. As a result, new theoretical models may take decades to confirm or refute.

To efficiently and effectively participate in this enterprise, subatomic physics research funding needs to be carefully managed. Funds must be available to support the small to mid-size capital investments and to provide the research support required to develop the next generation of experiments that advance the field. When new opportunities arise, significant capital is required for the construction of facilities and experiments. Success relies on all partners continuing their participation in the project. Therefore, coordination of funding sources for capital and operation is essential to ensure that new projects are carried through to completion.

1. Canadian Subatomic Physics in 2011

Approximately 240 full-time faculty are active in subatomic physics research, and the community has grown by approximately 10 percent over the past five years. Graduate student numbers are largely stabilized now after the substantial growth noted in the last plan.

The past five years have seen the community transitioning from construction of new major facilities and detectors to their exploitation in the Canadian effort to further knowledge in subatomic physics. The named priorities of the last LRP—ATLAS, T2K, the ISAC and SNOLAB experimental programs—are all operational and experimental results are flowing from all four. Research support funding for these projects has grown accordingly (Figure 7). During this same time, we have seen a decline in the fraction of the NSERC subatomic physics envelope available for exploring unique experiments with high discovery potential and for planning the next generation of projects (Figure 8). Indeed, by 2011 this had declined to 19 percent of the spending in the subatomic physics envelope. A specific impact of this decline has been the reduction of funding directed towards equipment, as can be seen in the more detailed breakdown of Figure 9. This is all an inevitable consequence of the NSERC subatomic physics envelope remaining practically unchanged over the last five years, which is bringing tremendous pressure to bear. The funds directed towards smaller, non-flagship experimental efforts have dropped by a factor of nearly two over the same time. Although these projects are smaller in scale than the flagship projects, they possess significant discovery potential in specific areas of research and may represent potential future directions for the broader Canadian subatomic physics community. The need for stable funding of the large flagship projects has placed enormous pressure on these smaller projects. Balancing these competing needs poses one of the greatest challenges to the community.

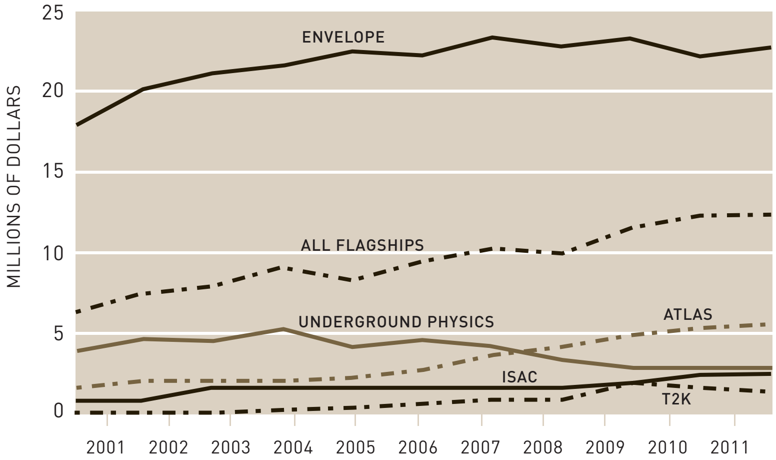


Figure 7: The funding allocated to the flagship activities from the NSERC subatomic physics envelope over the past 10 years.

It is a particular concern that the capacity of the NSERC subatomic physics envelope to fund capital expenditures has been dramatically reduced. This is reflective of a significant transition that has occurred over the past five years. This reduction in equipment funding in the subatomic physics envelope creates a significant risk. Subatomic physics has benefited enormously from the ability to award Research Tools and Instruments Grants - Category 1 (RTI-1), RTI-2, and RTI-3 when new research programs are entering a critical phase, particularly when the equipment needs are modest and/or do not fit well under any CFI programs. In the past five years, approximately $4.2 million have been awarded in RTI-2 and -3 grants to projects that were ineligible for funding through the CFI. Further, RTI-1 funding has allowed projects to deal with smaller real-time equipment needs that arise through the R&D process or because of a change in direction required of an experimental project. With the fraction of the NSERC subatomic physics envelope devoted to equipment at about five percent in 2011, it will be difficult to launch a new capital initiative where the nature and needs do not fit the CFI constraints. The lead time for such initiatives is five to10 years, as we saw with ATLAS. To integrate such equipment into an RTI-2 or -3 request from the NSERC subatomic physics envelope now, it would decimate the operations of projects which benefited from such investments years before. If the CFI route is indeed closed for these projects, it is therefore now impossible to initiate a major new capital investment in any international project without significantly reducing research support for projects we have brought to fruition over the past decade.

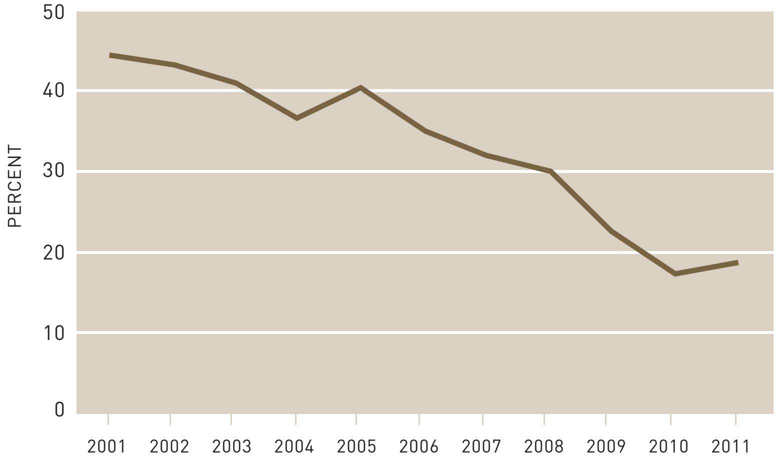


Figure 8: The fraction of the NSERC subatomic physics envelope available for seizing opportunities and planning for the next generation of experiments over the past 10 years. This fraction has been in precipitous decline due to the growing needs of the flagship projects.

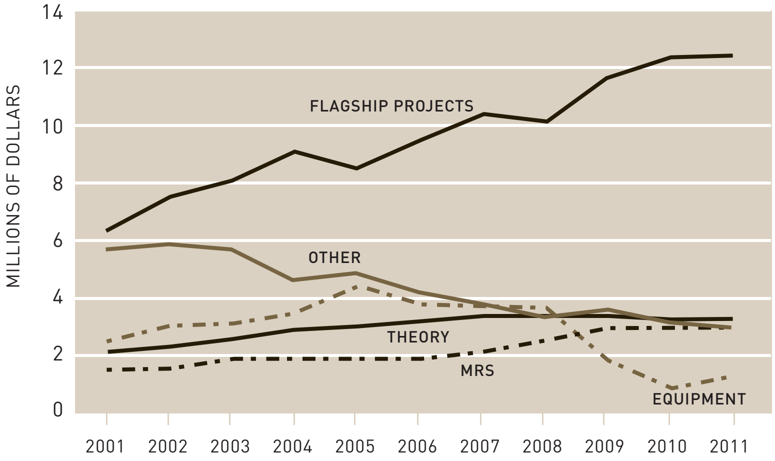


Figure 9: A detailed comparison of the different funding components of the NSERC subatomic physics envelope over the past 10 years. It is clear that funding for equipment has shrunk over this time. Similarly, the funding for other activities, specifically R&D and small discovery-potential projects, has shrunk by a factor of two in the past decade.

Where significant capital investments in Canadian-based experiments have been required, they have largely been met by CFI funding, with initial R&D efforts funded by the NSERC subatomic physics envelope. Indeed, CFI funding over the past 10 years has been, on average, equivalent to nearly 50 percent of NSERC funding to subatomic physics, distributed as shown in Figure 10. The injection of infrastructure funding to the community has been welcome, but has also created pressures; this will be discussed in Section 4 of this chapter.

We also need to recognize the demands the community places on the national facilities, particularly TRIUMF and SNOLAB. TRIUMF has long provided infrastructure support to the particle physics community, and TRIUMF houses the ISAC facility. TRIUMF successfully engaged the subatomic physics community in the development of the last five-year plan, which presented a coherent framework for the laboratory's support of Canadian subatomic physics. The strength of this vision resulted in TRIUMF maintaining constant funding for operations during a time of significant budget pressures on the federal government.

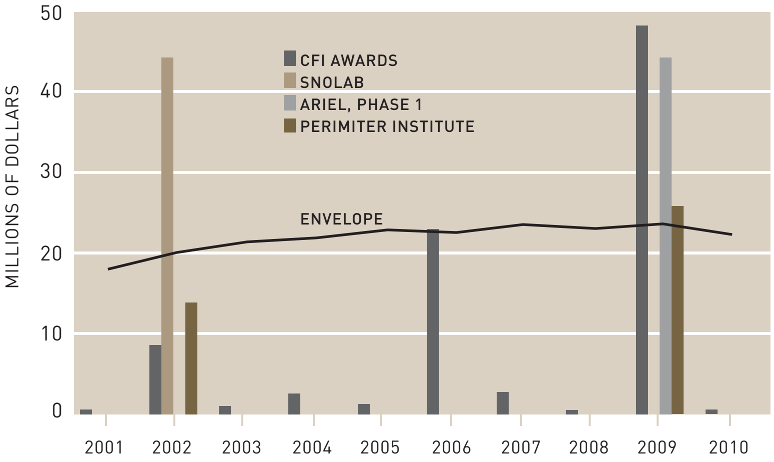


Figure 10: The value of CFI-funded infrastructure for subatomic physics projects between 2001 and 2010, compared to the NSERC subatomic physics envelope. The major facility projects—SNOLAB, Perimeter Institute, ARIEL Phase 1—are shown separately.

While this represented a substantial achievement for TRIUMF, it limited the ability of the laboratory to provide infrastructure support to the community. Completion and operation of ARIEL beyond 2016 will limit TRIUMF's ability to support major subatomic physics initiatives without an increase in federal funding for TRIUMF in its next five-year plan.

As for SNOLAB, the concern expressed in the last LRP remains, namely, how will the long-term operations of the facility be funded? A new CFI program offers some hope that this problem will be resolved, and this will be discussed further in Section 4 of this chapter.

The 2002 Reallocations Exercise resulted in an increase of the median NSERC Discovery Grants in subatomic theory by approximately 40 percent between 2001 and 2006. This increase was essential in allowing Canadian subatomic theorists to remain competitive internationally. At the same time, the top quartile of theoretical subatomic physics Discovery Grants increased by about 65 percent, indicating that rather than providing across-the-board increases, these funds were being preferentially directed to the most productive researchers. Since 2006, however, funding for theory has been essentially flat while new hires continue to put pressure on the NSERC subatomic physics envelope. Competition with the U.S. and abroad for personnel—particularly postdoctoral researchers and faculty—is intense, and it is therefore crucial for the field that funding for theorists be sufficient to keep graduate and postdoctoral support competitive internationally.

2. What the Future Holds

There is no doubt that a model for research support that does not grow with the size of the community will threaten Canadian leadership and negatively impact it in the longer term, and we are already at a critical juncture. We face a choice between leading in science now but ignoring the future, or continually building for the future while limiting our impact on ongoing projects. Neither is a wise path for the country as it seeks to lead in scientific innovation. This extends to the next phase in pursuing the community's physics priorities. For example, Canada would benefit from having significant impact in SuperB and the next step in flavour physics—an area where the country has led and could lead again. We will see within the next year whether the Higgs boson is found, or whether a radical reconsideration of the Standard Model is required. This will impact discussions of an upgrade to the LHC and the impetus for a linear collider project. Canada needs to be positioned to respond to these international decisions and directions while simultaneously pursuing the science influencing these decisions. The NSERC subatomic physics envelope needs to be expanded for this to happen.

The community could potentially free-up funds in the NSERC subatomic physics envelope by reducing activities on flagship experiments, eliminating R&D activities, and reducing activities on smaller projects with high discovery potential. However, this would substantially dilute the Canadian presence on experiments where Canada has made major investments over the past 10 years (or more), possibly even creating a situation where there is little Canadian effort (let alone leadership) at national facilities such as ISAC and SNOLAB. This would represent a major loss of both financial and intellectual investment to the country.

3. Measuring Our Success

We are aware that NSERC has charged the Canadian Council of Academies with studying possible metrics for scientific activity and impact that could be used in a future reallocations exercise. As has been noted throughout this plan, the workings of the subatomic physics community are somewhat unique, especially the large scale of international collaboration and long-term planning and investment. Indeed, we are celebrating the 20th year of the subatomic physics envelope—a unique structure within NSERC that continues to prove itself crucial, time and time again, as the subatomic physics community has progressed through successive long-range plans. We would welcome the opportunity to provide input in helping develop appropriate metrics to recognize and balance our unique characteristics.

Any method seeking to measure research quality and productivity in subatomic physics needs to account for the large-scale and long-term nature of research projects in this discipline. Metrics appropriate for other fields, in which an experiment can be conceived, performed, analyzed, and published by a small group within one or two years, may not be suitable. Researchers may spend many years designing and building an experiment, resulting in a low publication rate during the period. For example, the ATLAS collaboration formed in 1992 and data-taking only began in 2009. Theoretical research publications may wait many years for significant citations because of the time scale for developing experiments capable of testing the new theories. Experimental research publications may include hundreds or thousands of scientists in the author list, making it difficult to attribute specific contributions to individuals or groups. For large collaborations, there are internal indicators for research productivity, such as appointment to leadership positions (typically for senior researchers) and selection to speak on behalf of the collaboration at conferences (typically for younger researchers). Another record of research contributions comes in the form of unpublished internal papers, written by small groups that describe, in detail, the various elements that were necessary to produce the results that appear in published papers. Research quality and productivity are reflected by the record of HQP training, since disciplines with strong research programs generally attract excellent students. In highly collaborative disciplines like subatomic physics, the learning environment for HQP is enhanced through direct contact with expert team members from around the world. Measurements of research quality derived from HQP outcomes should take into account the training benefits of collaborative research.

4. Optimizing Relationships Between Organizations (CFI, Compute Canada, etc.)

As we have seen throughout this plan, the unique nature of subatomic physics typically requires large international collaborations building and operating sophisticated instruments for experiments that are operated for many years and address questions about the very nature of our universe. NSERC has recognized the unique nature of subatomic physics by implementing a funding envelope model, which allows the community to plan and prioritize. This has been very successful and has allowed the Canadian community to be central in the global subatomic physics enterprise.

The CFI has been a transformative addition to the Canadian funding environment. It has allowed Canadians to develop world class infrastructure and facilities. Subatomic physics groups have demonstrated that they meet the standards of excellence and impact for Canada and have been significant beneficiaries. The CFI has been the major source of funding for key facilities (SNOLAB and ARIEL, along with the PI), besides infrastructure-supporting flagship experiments (e.g., Tier 1 and Tier 2 computing centers for ATLAS, SNO+, and DEAP-3600).

The community is now engaged in research utilizing the significant investments in subatomic physics infrastructure supported by NSERC and the CFI in the past 10 to15 years. As has been noted, the funding for research support from the NSERC subatomic physics envelope has remained constant. This imbalance will continue to cause significant problems for the proper utilization of the infrastructure and for considering how to best plan and do research in Canada.

The CFI-Major Science Initiative (MSI) has been very welcome news. The last LRP noted the subatomic physics community's concern regarding the source of operating funds for SNOLAB. Given limited funds, it was impossible to foresee a scenario where the priority given in that plan to the SNOLAB experimental program could be realized without new funds being found to operate the facility. The Long-Range Planning Committee, on behalf of the Canadian subatomic physics community, is grateful to NSERC and the CFI for working together to provide interim support towards SNOLAB's operations while a framework for the support of Major Science Initiatives was being developed. The CFI-MSI initiative might help finally resolve that concern. There is some question as to where the required matching funds will be found, though provincial governments have already demonstrated commitment to the large CFI facilities positioned within their territories through contributions to the operating budgets. Granting agencies are also eligible partners, though it is clear that the NSERC subatomic physics envelope or any other component of the NSERC Discovery suite of programs, whose objective is to support research activities, is ill-suited to support the operations and maintenance costs of a national laboratory such as SNOLAB (or TRIUMF). To think otherwise would revive the conflict seen in the last plan between funding SNOLAB operations with no direct scientific or discovery return, and the experiments to be housed at the facility which aligns with the scientific priorities of the community. We will watch with interest as the competition proceeds and hope that the CFI-MSI program leads to sustained solutions to the funding of these large infrastructure sites.

Compute Canada has also been a significant addition to Canadian capabilities, with the provision of world-class computer facilities to Canadian researchers. TRIUMF provides significant resources to Canadian subatomic physics—both through the operation of the TRIUMF-based facilities, and the enabling of research at other laboratories—such as ATLAS, T2K, and SNOLAB.

As we look to the future, working within a paradigm with multiple agencies and a complex funding paradigm offers several challenges. One issue is how to effectively balance the priorities and restrictions on the use of funds from different funding agencies with the priorities of the community. The primary source of funding for research activities is by far the NSERC subatomic physics envelope, and we have seen an ever-increasing fraction of that envelope directed towards ongoing research support for existing projects. It is thus crucial for the next generation of Canadian subatomic physics projects that CFI funding be made available in the future for internationally sited infrastructure involving the Canadian subatomic physics community, in addition to nationally sited infrastructure.

Many experimental projects require an integrated approach to managing R&D, capital funding, and research support. This was the original purpose of the NSERC subatomic physics envelope—to let the community manage funds through the ebb and flow of the different stages of large, long-term projects. From a researcher's perspective, a project is organized systematically from an R&D phase to construction, and then on to making measurements in the quest for new physics understanding. This process was relatively straightforward when managed solely under the NSERC subatomic physics envelope, but the new reality may involve both NSERC and the CFI together, or separately, at different phases of the project. It is further complicated if the project requires support from TRIUMF in order to proceed. TRIUMF's potential support for a project has been a part of the consideration given by NSERC when determining funding, so a degree of integration has been put in place that we would like to see to continue. A similar model may well evolve with respect to experiments housed at SNOLAB. We also see examples where Canadian subatomic physicists receive support from international laboratories to develop new experiments.

There are non-trivial issues associated with this coordination, specifically when the CFI is funding significant capital associated with a larger project. The maximum benefit to Canada and the research program would see a holistic approach to the phasing of R&D (NSERC) and construction (CFI) of major research infrastructure, especially with respect to engineering and science reviews. Other bodies play a role in this effort as well, particularly the host laboratories—TRIUMF and SNOLAB. Thus, it would be to Canada's strategic advantage if there was coordination between organizations when funding major projects in subatomic physics.

A further question arises when large projects are to be housed off-shore—a looming issue as Canadian subatomic physics looks to the next generation of large international experiments. It is unclear what mechanisms exist within the CFI to allow for a funding proposal to CFI that would authorize installation of equipment components at a large off-shore experiment, as long as ownership remains with Canadian universities. Furthermore, the community would welcome the opportunity to work with the CFI so that the LRP can assist the organization to maximize the benefits of its infrastructure investments in subatomic physics—be they in Canada or at international facilities.

There is a parallel problem of coordination of effort between experimental programs, Compute Canada and others. As noted, Compute Canada manages the large platforms, but the subatomic physics research program must ensure that it has the appropriate priority of access to the relevant facilities, and also be able to avail itself of the (highly specialized) technical support required for its applications.

All organizations are working hard to support Canadian science, and the community values their support. Our goal is to ensure that all are working together to ensure maximum scientific impact and return from the Canadian investment in subatomic physics.

7

Supporting Innovation in Subatomic Physics

1. Budgetary Estimates

The Need to Support R&D

The subatomic physics community has been successful in its goals to focus its activities on flagship projects and is now positioned to reap the scientific benefits of past investments, while simultaneously facing the need to prepare for the next generation of projects. In reaching this point, the community now faces many pressures. As noted earlier in the document, the subatomic physics envelope faces severe challenges in its ability to manage projects in subatomic physics over the typical 10 to 20 year timescale—from conception to reaping the scientific reward. In particular, as we look to the R&D required for the next generation of projects, the available funding for RTI grants has fallen to five percent of the envelope—well below the level of 15 percent that was required to provide for the R&D associated with the current flagship projects. As has been described earlier in the plan, this drop was unavoidable in light of the need to provide the funds required for research activities associated with the flagship projects. If Canada is to continue to lead in the next generation of projects of national and global importance, the community must have access to appropriate resources for R&D. It is therefore an utmost priority to see additional funds added to the subatomic physics envelope to prepare for continued Canadian leadership in subatomic physics through the next 20 years or more. Based on the 2011 funding of the subatomic physics envelope, increasing the RTI component from five to 15 percent requires that the annual funding allocation for the subatomic physics envelope be permanently increased by approximately $2.5 million. As noted earlier, the need for these funds is immediate. If this issue remains unresolved over the timeframe covered by this plan, the effects on the Canadian subatomic physics program could be catastrophic.

Maintaining a Restrained Yet Efficient Program

We also cannot ignore pressures that exist aside from any upgrades or new initiatives within the flagship projects. Over the past 10 years, the funding to the flagship research programs has grown by an average of 6.5 percent per year. This growth tracks the increased research activity associated with these projects, moving from the development and construction phases covered by previous long-range plans towards being fully operational over the course of this plan. Throughout this time, the Grant Selection Committees (GSC), and then the Evaluation Sections (ES), worked to ensure that these funding increases were absolutely vital to the success of these projects. They were very concerned about the consequence of these necessary increases for the rest of the subatomic physics envelope, and these concerns were repeatedly expressed in the reports of the Chairs to NSERC and the community. These increases have been driven by the flagship projects approaching the stage of data-taking and science exploitation, which require a larger involvement of HQP while facing competitive pressures in recruiting them, as well as an expanded participation of the Canadian community. The community was very careful in making use of the most effective funding mechanisms to support this growth in participation and reach a critical mass in each of the flagship projects in order to be a recognized contributor and leader. In particular, the community has judiciously sought support from the CFI for the construction of major infrastructure (post-R&D). However, the community and the subatomic physics envelope face continuous pressures to ensure a constrained yet effective support to research activities and the accompanying HQP. The flagship projects have not yet reached their "maturity," and they still need increased support. If it is not realistic to argue to maintain a 6.5 percent growth, the pressures on the Canadian subatomic physics community are nonetheless real. Indeed, this draws attention again to the fact that there is little room left within the envelope to support the R&D activities that will ensure the vitality of the Canadian program 15 to 20 years from now.

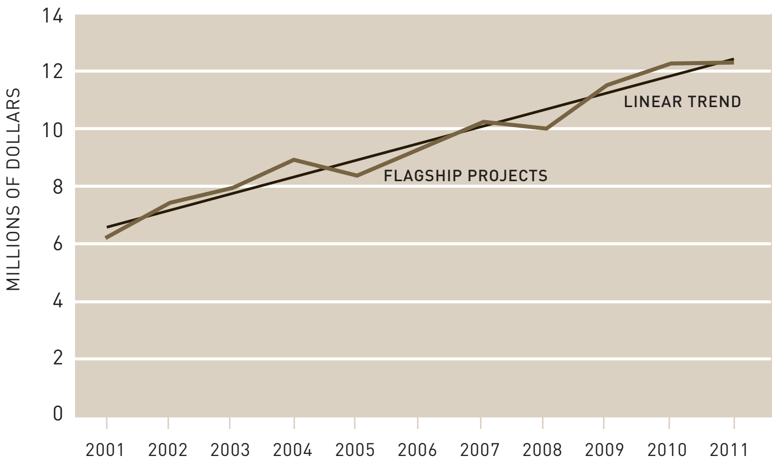


Figure 11: Linear trendline fit to flagship project funding. Growth averages 6.5 percent per year in this period.

If additional funds are made available for R&D through the RTI component of the subatomic physics envelope, we would expect some increase in research activity directed at the next generation of projects. This will help quench the average growth rate of funding to the flagship projects, as members of the community will be expected to re-focus their activities. Still, one could prudently make use of the national inflation rate (averaged over the last five years/2006-10) as a measure of what the average increase could be in supporting the flagship projects. This average rate is 1.7 percent,[1] which represents a need for the addition of $1.0 million per year in funding to the support provided to these flagship projects, by 2016. The subatomic physics envelope cannot sustain the pressure to provide this funding. These funds would need to be new to the envelope.

As shown in Table A, the overall impact of the various pressures on the subatomic physics envelope for research support would require an injection of $3.5 million by the end of the five years covered in this plan. The development work towards next-generation projects may place further demands that cannot yet be fully quantified. We recognize that this is challenging in the existing government funding environment, but are committed to working with all relevant parties to garner increased support for NSERC's Discovery programs in general, and for the subatomic physics envelope in particular.

Table A: Summary of critical funding needs for the NSERC subatomic physics envelope over the next five years

Project	Permanent Funding Increase Needed for the Subatomic Physics Envelope
Restore funding for R&D through RTI funding to 15% of the subatomic physics envelope	$2.5 million
Funding to reap scientific reward from investments in flagship projects	$1.0 million
Total	**$3.5** million

New opportunities

There are exciting opportunities for next-generation projects consistent with the focussed objectives of the Canadian subatomic physics community, and each has a significant cost which must begin to be addressed within the next 5 to 10 years or opportunities will be lost. These projects will require both capital funding and R&D support. A summary of the capital costs can be found in Table B.

[1] Statistics Canada Consumer Price Index—Historical Summary, http://www40.statcan.ca/l01/cst01/ECON46A-eng.htm

Table B: Capital costs required from various agencies to develop and participate in new opportunities

	Direct Capital Cost[2] (Estimated)	Approximate Timeframe
ATLAS Upgrade	$9 million	2014-16
SuperB	$2 million	2013-15
T2K upgrade	$1 to 2 million	2013-15
EXO	$15 million	2015-18

The R&D of Canadian components for these experiments will need to be funded through the NSERC RTI Grants as just presented. When it comes to the final purchase of capital equipment, EXO is potentially a CFI-funded project (assuming EXO is sited at SNOLAB) under existing precedents. The other three are subject to clarification on CFI funding of offshore projects. In all cases, the envelope has lost the flexibility to absorb the funding of the full capital contributions as it did for ATLAS, T2K, BaBar, and several detectors related to ISAC, even if the funds available are increased for RTI applications in the subatomic physics envelope, as proposed here. If development of these projects requires infrastructure support from TRIUMF, there needs to be further coordination with the laboratory in order to secure that support.

We must emphasize that these initiatives will all increase the research potential for Canadian subatomic physics, but seizing that potential will require increased research capacity. There will be a need for enhanced research support associated with the development, construction and, ultimately, discovery phases of these projects.

TRIUMF is preparing for ARIEL Phase II.[3] This project will increase (three-fold) the simultaneous beams to experiments in ISAC and ISAC-II. This would not necessarily triple the research needs of the ISAC groups, but would certainly increase them if they are to exploit the advantages ARIEL presents to Canada. A better sense of these needs will be developed through the next TRIUMF five-year planning exercise, which will begin soon. It may, in fact, be possible for TRIUMF to provide direct guidance to NSERC about the additional research-support needs arising from ARIEL Phase II.

The ATLAS and T2K upgrades would be undertaken by the existing groups. The new experimental initiatives on the horizon—SuperB and EXO—will also require new research support. We can anticipate that SuperB would likely require funding at least consistent with BaBar funding at its peak (about $1 million per year) when it reaches full installation and operation phases. EXO is somewhat more difficult to predict, as many decisions are required before the scope of Canadian participation can be determined.

[2] Funding estimates from the Institute of Particle Physics (IPP) brief

[3] Phase I of the ARIEL project is already funded through contributions from the Government of Canada and the Government of British Columbia. Under the understanding between TRIUMF and NSERC, resources to complete ARIEL Phase II will come from outside NSERC with contributions from Industry Canada, other agencies of the Government of the Canada, and international investments.

Appendix

The Long-Range Plan for Canadian Subatomic Physics: 2011-16

Terms of Reference

I. Context

Under NSERC's aegis, the Canadian subatomic physics community establishes its scientific, and thus funding, priorities through five-year Long-Range Plans (LRPs). These plans advise NSERC and the Subatomic Physics Evaluation Section on the community's priorities for both current and future endeavours. The most recent Long-Range Plan covered the period 2006-11, in addition to providing an assumption-based forecast for the period 2011-16. Since then, the timelines of some experiments and future projects have evolved, new funding for major equipment has been secured, and TRIUMF's new five-year plan has been developed (and its funding should be known in early 2010). New research opportunities may also have emerged. A new LRP exercise will be conducted. It will cover the period 2011-16 and include a look ahead to 2021.

II. Committee

The LRP process will be driven by the Canadian subatomic physics community. A committee will be asked to review this community's input and to formulate the LRP. The LRP Committee will be composed of an appropriate number of experts who will cover the main sub-disciplines reviewed by NSERC's subatomic physics Evaluation Section, including both experimental and theoretical aspects—nuclear physics, nuclear astrophysics, physics of elementary particles and fields, and particle astrophysics. The Committee will be chaired by a senior member of the research community with an extensive knowledge of the Canadian and international subatomic physics research environments. The membership may have some overlap with that of the previous LRP Committee to ensure continuity.

The LRP Committee will also include ex officio members who will only be observers and resources for the other members. These ex officio members are:

- the Chair of the subatomic physics Evaluation Section;
- the Director of the Canadian Institute of Nuclear Physics;
- the Director of the Institute of Particle Physics; and
- TRIUMF's Associate Director.

Observers from other agencies will be invited to attend.

The LRP Committee may choose to hold certain closed sessions without the presence of ex officio members or observers.

NSERC representatives will act as observers and resources at all times.

III. Mandate

Taking into account: the ever-increasing internationalization of projects and collaborations in addressing the fundamental questions of subatomic physics; the concurrent requirement to maintain and further develop world-class domestic research programs and infrastructure; the established expertise and strengths of the Canadian community; and the recognition of the fact that the Canadian subatomic physics community cannot be involved in all research endeavours (as stated by the last LRP Committee in its report). The Committee is asked to identify subatomic physics scientific ventures and priorities that should be pursued by the community on a five- to 10-year horizon that would ensure continuous Canadian global scientific leadership. Budgetary estimates must also be provided, including funding ranges for prioritized endeavours. These ranges should include funding levels that would allow for a restrained, yet efficient, contribution to the ventures, and levels that would enable a more extensive contribution.

The Committee's assessment will be based on a broad consultation with the Canadian subatomic physics community. It must be guided only by the current and future science in subatomic physics. The Committee will have to assess the feasibility, technical readiness and risks associated with particular endeavours. It is crucial that such an assessment be made through a fair and rigorous process.

The Committee is also asked to consider and discuss factors that affect the subatomic physics community and to make recommendations on how to possibly lessen any negative impacts they may have, or enhance any positive ones. Examples of such factors include, but are not limited to, NSERC programs other than those in the purview of the subatomic physics Evaluation Section, the relationship between NSERC and other agencies and organizations, and the activities of national research organizations.

IV. Process and Timeline

The LRP Committee membership will be completed by the end of May 2010, and a kick-off meeting will be held immediately after.

The Canadian Institute of Nuclear Physics (CINP) and the Institute of Particle Physics (IPP) will be tasked to prepare briefs for the LRP Committee. These briefs must summarize the scientific vision and priorities put forward by the sub-communities they represent and serve, including both experimental and theoretical facets. Overall recommendations may also be included in the briefs. It is expected that each institute will broadly consult with the sub-communities through various formats, and ensure a fair and rigorous process. The briefs are to be submitted to NSERC no later than September 1, 2010, and they will be forwarded to the LRP Committee. The CNIP and IPP must ensure that the briefs are available to the entire community through their public Web sites. Eventual responses to the briefs by individuals or organizations would be accepted and should be submitted to NSERC; they would be forwarded to the LRP Committee. Throughout the process, the LRP Committee may also solicit additional input from various sources, as it sees fit.

The LRP Committee will hold public consultations (town hall meetings) during the fall of 2010, after receiving the briefs. Face-to-face or phone meetings of the Committee will then be held up to the spring of 2011. A final report is to be provided to NSERC no later than September 1, 2011.

V. Deliverables

The LRP Committee will submit its final report to NSERC no later than September 1, 2011. The report will be publicly released, thereafter, in both official languages.

VI. Conflicts of Interest and Confidentiality

All members must strictly comply with the terms of the statement on ethics for NSERC selection committees and panels. Moreover, for the purpose of this exercise, a member will be considered to be in a situation of conflict of interest during a discussion on prioritization of a specific endeavour that would directly benefit the member or the member's organization.

VII. Financial Support

NSERC will provide the LRP Committee with financial support for the purpose of organizing appropriate meetings, for the travel of Committee members to these meetings and for the preparation of the report.

Long-Range Planning Committee Membership

- **Malcolm Butler (Chair)**
  Carleton University
  Nuclear physics theory; neutrino astrophysics; low-energy tests of quantum chromodynamics; astrophysics
- **Äystö, Juha**
  University of Jyväskylä, Finland
  Experimental nuclear physics; nuclear structure; reactions and decays of nuclei far from stability; radioactive ion beams; heavy-ion physics; techniques of nuclear spectroscopy; applied accelerator physics; nuclear astrophysics; atomic physics; high-precision measurements on fundamental constants and interactions; laser-assisted methods in nuclear physics; environmental detection methods
- **Burgess, Clifford**
  McMaster University/Perimeter Institute for Theoretical Physics
  Formal theory; high-energy particle theory; strings and branes; effective field theory techniques; Dark Matter and Dark Energy; cosmology
- **Garrett, Paul**
  University of Guelph
  Experimental nuclear physics; nuclear spectroscopy; gamma-ray, neutron, and charged-particle detection; nuclear instrumentation; nuclear reactions; beta decay; collective and single-particle excitations in nuclei
- **Hallin, Aksel**
  University of Alberta
  Experimental high-energy physics; Dark Matter; neutrino physics and astrophysics; particle astrophysics
- **Huber, Garth**
  University of Regina
  Experimental intermediate energy nuclear physics; studies of hadronic structure; quantum chromodynamics
- **Karlen, Dean**
  University of Victoria
  Experimental high-energy physics; detector development; linear accelerators; neutrino properties
- **Luke, Michael**
  University of Toronto
  Elementary particle theory: b quark physics; quantum chromodynamics; heavy quarks; effective field theories

- **O'Neil, Dugan**
  Simon Fraser University
  Experimental high-energy physics; fundamental particles and their interactions; proton-antiproton collisions; ATLAS experiment; high performance computing
- **Robertson, Steven**
  McGill University/Institute of Particle Physics
  Experimental high-energy physics; collider-based experimental searches for evidence of physics beyond the Standard Model; searches for rare decays of B mesons; drift chamber research and development; High-Level Trigger physics algorithm development
- **Scholberg, Kate**
  Duke University, U.S.
  Experimental high-energy physics; astrophysics; cosmology; low background (underground) experiments; neutrino physics

Glossary

ALPHA (Antihydrogen Laser PHysics Apparatus): An experiment at CERN trapping and studying the properties of antihydrogen atoms.

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch): A high-energy neutrino detection experiment that is being built 50 kilometres off the coast of France, about 2,400 metres below sea level.

ARIEL (Advanced Rare IsotopE Laboratory): A project to broaden TRIUMF's capabilities to produce rare isotope beams and to showcase new Canadian accelerator technology.

ATLAS (A Toroidal LHC ApparatuS): A particle physics experiment at the Large Hadron Collider at CERN.

ATRAP (Antimatter TRAP): An experiment at CERN trapping and studying the properties of antihydrogen atoms.

BaBar (B-Bbar detector): Experiment at the SLAC National Accelerator Laboratory to study the properties of B and Bbar mesons at high-precision.

BNL (Brookhaven National Laboratory): One of 10 national laboratories overseen and primarily funded by the Office of Science of the U.S. Department of Energy, located in Upton, New York, U.S.

CALICE (CAlorimeter for the LInear Collider Experiment): A detector proposed and under development for the International Linear Collider.

CARIBU (CAlifornium Rare Isotope Breeder Upgrade): A facility for creating neutron-rich rare isotopes at Argonne National Laboratory in Illinois, U.S.

CDF (Collider Detector at Fermilab): An experiment to study proton-antiproton collisions at the Tevatron, located at the Fermilab in Illinois, U.S.

CDMS (Cryogenic Dark Matter Search): A Dark-Matter experiment currently based at the Soudan Underground Laboratory in Minnesota, U.S.

CERN (Centre European pour la Recherche Nucleaire): The European Organization for Nuclear Research, based in Geneva, Switzerland.

CINP: Canadian Institute of Nuclear Physics

CLEAN (Cryogenic Low Energy Astrophysics with Noble gases): A Dark Matter experiment being installed at SNOLAB.

CLEO: An early experiment to study the properties of mesons with b quarks at Cornell University in the U.S.

CLIC (Compact Linear Collider): An R&D project aimed at developing cost-effective technology for the International Linear Collider.

CMS (Compact Muon Solenoid experiment): A particle physics experiment at the Large Hadron Collider at CERN.

COUPP (Chicagoland Observatory for Underground Particle Physics): A Dark Matter experiment, based at the Fermilab in Illinois, U.S.

CPT (Canadian Penning Trap): The CPT spectrometer is designed to provide high-precision mass measurements of short-lived isotopes. It is located at the Argonne National Laboratory in Argonne, Illinois.

D0: Named for its location on the accelerator ring, an experiment to study proton-antiproton collisions at the Tevatron, located at the Fermilab in Illinois, U.S.

DEAP (Dark matter Experiment using Argon Pulse-shape discrimination): A Dark Matter experiment based at SNOLAB.

DESCANT (DEuterated SCintillator Array for Neutron Tagging): A neutron detector array to be used at ISAC.

DESY (Deutsches Elektronen-SYnchrotron): A particle accelerator facility, based in Hamburg, Germany.

DRAGON (Detector of Recoils And Gammas Of Nuclear reactions): A detector designed to measure the rates of nuclear reactions important in astrophysics, based at ISAC-I.

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

EXO (Enriched Xenon Observatory): An experiment seeking to measure neutrinoless double beta-decay.

FAIR (Facility for Antiproton and Ion Research): An accelerator facility for studying nuclear structure and nuclear matter, based at GSI.

Fermilab: The Fermi National Accelerator Laboratory in Illinois, U.S.

FRIB (Facility for Rare Isotope Beams): A new user facility for nuclear science, operated by Michigan State University, U.S.

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

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

GSI: The GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany.

Hyper-Kamiokande: A proposed project for a half-megaton water Cherenkov detector at the Kamioka Observatory in Japan.

IceCube: A high-energy neutrino detector embedded in the ice at the South Pole.

ILC (International Linear Collider): A proposed electron-positron linear collider, currently under research and development.

IPP: Institute of Particle Physics (Canada).

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

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

Jefferson Lab: The Thomas Jefferson National Accelerator Laboratory in Virginia, U.S.

J-PARC (Japan Proton Accelerator Research Complex): An accelerator facility for nuclear and particle physics research in Japan.

KEK (Kou Enerugi Kenkyu Kiko): A high-energy accelerator facility in Japan.

K2K (KEK to Kamioka): A long-baseline neutrino oscillation experiment in Japan.

LBNE (Long Baseline Neutrino Experiment): A proposed experiment to study neutrino oscillations between Fermilab and the Sandford Underground Laboratory in North Dakota, U.S.

LEP (Large Electron Positron Collider): A retired high-energy electron-positron accelerator based at CERN.

LHC (Large Hadron Collider): The world's highest energy particle accelerator, based at CERN in Switzerland.

MAMI (Mainz Microtron): An electron accelerator facility, based in Mainz, Germany.

Majorana: An experiment whose objective is to study double beta-decay in ^{76}Ge.

MINOS (Main Injector Neutrino Oscillation Search): A neutrino oscillation experiment, based at Fermilab in Illinois, U.S.

MOLLER: An experiment to measure the parity-violating asymmetry in electron-electron (Møller) scattering at Jefferson National Laboratory in Virginia, U.S.

PEP-II (Positron Electron Project): An electron-positron collider facility based at the SLAC National Accelerator Laboratory in California, U.S.

PICASSO (Project In CAnada to Search for Supersymmetric Objects): A Dark Matter experiment based at SNOLAB.

QCD (Quantum ChromoDynamics): The theory describing the interactions between quarks and gluons.

RCNP (Research Centre for Nuclear Physics): A national centre for nuclear physics, based in Osaka, Japan.

RHIC (Relativistic Heavy-Ion Collider): A high-energy heavy-ion collider facility based at Brookhaven National Laboratory in New York, U.S.

RIBF (Rare Isotope Beam Factory): A new user facility for nuclear science, located at RIKEN.

RIKEN: A Japanese organization that carries out high-level experimental and research work in a wide range of fields—including physics, chemistry, medical science, biology and engineering.

SLAC National Accelerator Laboratory: Originally a particle physics research center, SLAC is now a multi-purpose laboratory for astrophysics, photon science, accelerator and particle physics research based in Stanford, California.

SNO (Sudbury Neutrino Observatory): An experiment based in Sudbury, Canada, that proved, conclusively, that neutrinos change flavour (oscillate) as they travel from the Sun to the Earth.

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

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

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

SuperB: A next-generation B meson factory, to be built in Italy.

SuperCDMS: A proposal for a larger version of the CDMS experiment.

Super-K (Super-Kamiokande): A water Cherenkov detector used for neutrino physics and proton decay, based at the Kamioka Observatory in Japan.

T2K (Tokai to Kamioka): A particle physics experiment studying neutrino oscillations, based in Japan.

TACTIC (TRIUMF Annular Chamber for Tracking and Identification of Charged particles): A device used in conjunction with TUDA.

TEVATRON: The second-highest energy particle accelerator in the world, located at Fermilab in Illinois, U.S.

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

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

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

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

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

TWIST (TRIUMF Weak Interaction Symmetry Test): An experiment to measure the decay properties of muons to high precision.

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

VECC (Variable Energy Cyclotron Centre): R&D unit of India's Department of Atomic Energy; one of the constituent institutions of Homi Bhabha National Institute.

VERITAS (Very Energetic Radiation Imaging Telescope Array System): A detector for high-energy gamma rays from astrophysics sources, based in Arizona, U.S.

WIMP (Weakly Interacting Massive Particle): A class of hypothetical particles that is a candidate for the non-baryonic Dark Matter.

XEP (Xenon Electroluminescence Prototype): A prototype detector studying the gas-phase option for the EXO experiment.

ZEUS: An experiment at DESY studying electron-proton collisions at high energy.

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