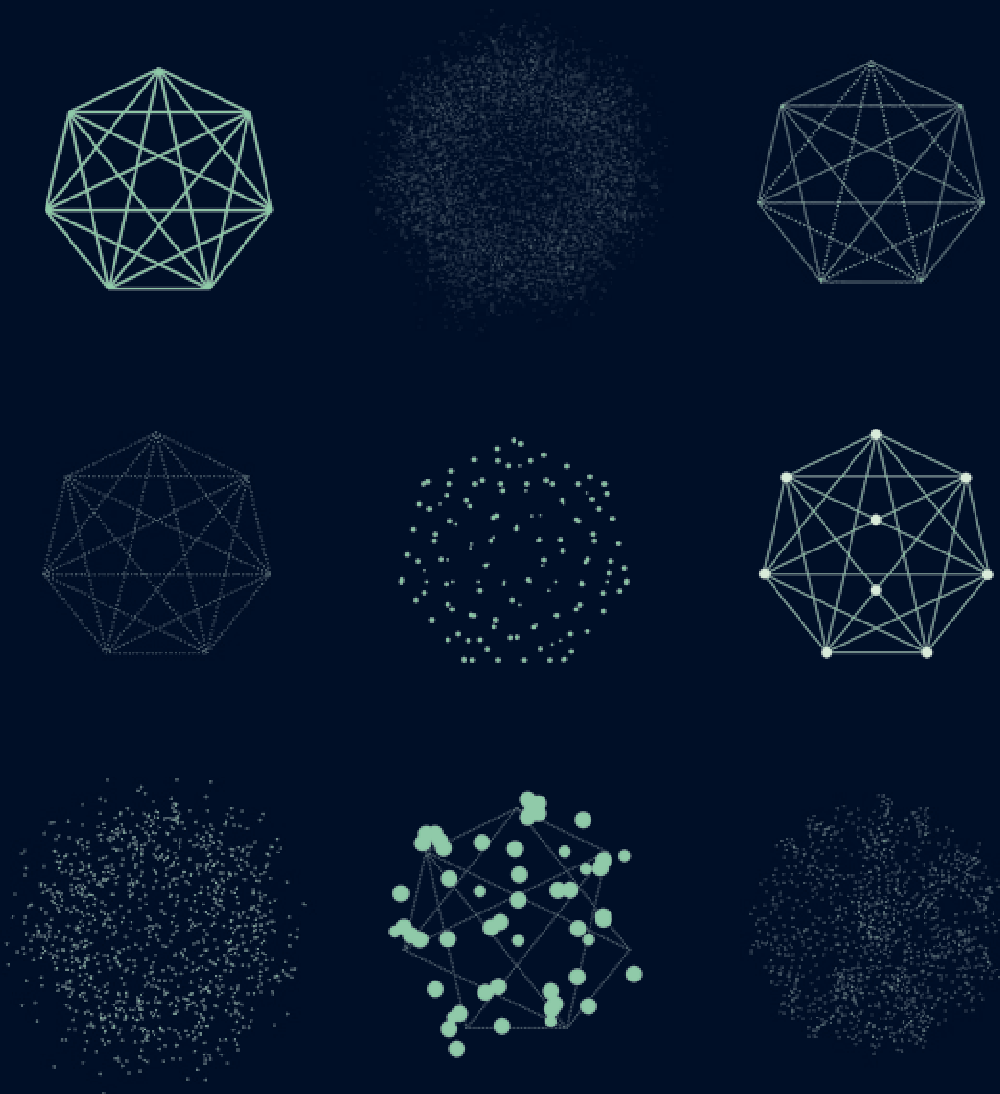
Canadian Subatomic Physics Long Range Plan

2017-2021



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1. Executive Summary

Subatomic physics research is a quest to discover and understand the basic laws that govern the universe. When going beyond the atomic scale and examining matter at distances smaller than nuclei, intriguing patterns and phenomena emerge that reveal the fundamental nature of matter and forces. Remarkable progress has been made over the past 100 years of subatomic physics research, but a complete theory remains an elusive and exciting goal.

Canadian subatomic physics has an enviable reputation, garnering several recent major international awards acknowledging projects with leading or significant Canadian involvement. The 2013 Nobel Prize in Physics and the 2013 Special Breakthrough Prize in Fundamental Physics recognized the discovery of the Higgs Boson by the two large experiments at CERN, including ATLAS, in which Canada is a significant partner. Arthur McDonald (Queen's University), in sharing the 2015 Nobel Prize in Physics with Takaaki Kajita (University of Tokyo) for the discovery of neutrino oscillations, was honoured for his leadership of the highly successful SNO experiment, which involved many Canadian and international collaborators. The 2016 Breakthrough Prize in Fundamental Physics also recognized SNO along with four other experiments, including T2K, which has a large Canadian team.

Excellence of Canadian subatomic physics has also been recognized in recent national science assessments. The Council of Canadian Academies' 2012 report, "The State of Science and Technology in Canada," identified Nuclear and Particle Physics as one of the sub-fields in which Canada leads the world in scientific impact. The Canadian government's 2014 "Science and Technology Report" included the Higgs Boson discovery in its compilation of "Canadian pioneers in scientific and technological achievement."

Canadian subatomic physics developed through the organization of cohesive groups that work on the most pressing questions in the field and has now reached a new level of excellence, with researchers playing leading roles. A solid reputation of following through on its commitments has made Canada a welcome partner to collaborate with on leading international ventures. The impacts of this research go beyond expanding humanity's understanding of the universe; they also bring tangible benefits to society by inspiring youth and attracting them to scientific and technical careers, by training highly qualified personnel, and by developing advanced technology with applications in areas such as healthcare, natural resource development, security, and energy.

To ensure Canada's continued success in subatomic physics, the Canadian Subatomic Physics Long Range Plan Committee has developed recommendations for the 2017-2021 period in consultation with the broader community. The recommendations flow from the following key principles, which have brought the field in Canada to where it is today:

- participate at the highest possible levels, assume leadership roles, and tackle the most important research problems;
- ensure high impact by concentrating effort and taking on major responsibilities in world-leading subatomic physics projects;
- strategically participate in innovative smaller-scale projects with the potential of significant discovery;
- maintain capacity and flexibility to take advantage of new scientific opportunities as they arise;
- fully engage undergraduate, graduate, and post-doctoral students in all aspects of scientific research; and
- deliver on promises to Canada and international research partners.

The scientific and policy recommendations appearing in the main body of this report are presented in this chapter, with brief preambles added for context. The recommendations are not ordered by priority.

1. RECOMMENDATIONS: CANADIAN SUBATOMIC PHYSICS RESEARCH PLAN

Research in theoretical subatomic physics drives and develops understanding of the big questions in the field, provides the foundation for interpreting experimental results, and suggests new paths for discovery.

SCIENTIFIC RECOMMENDATION

Maintain strong support for research in theoretical subatomic physics.

Canada is significantly involved in a number of world-leading facilities and experiments at the frontiers of subatomic physics. These projects, playing instrumental roles in helping discover the answers to the big questions in the field, have been planned and developed over a period of decades and were identified as the highest priorities in previous subatomic physics long range plans.

SCIENTIFIC RECOMMENDATION

Provide continued support and resources to the following ongoing flagship facilities and experiments, now producing scientific results thanks to significant coordinated Canadian and international efforts and financial investments, to ensure that they fully realize their potential:

- TRIUMF radioactive beam facilities and associated experiments. The anticipated tripling of beam delivery with ARIEL over the next 5 years will significantly increase scientific output, training opportunities, and broader impacts.
- SNOLAB and its experiments, beginning their search for dark matter interactions and neutrinoless double-beta decay, phenomena never before observed.
- ATLAS experiment, now exploring proton collisions near the ultimate energy and with the increasing luminosity of the Large Hadron Collider.
- T2K experiment, studying neutrino properties with increasing precision as the neutrino beam intensity continues to ramp up.

Experimental efforts with smaller-scale Canadian participation can offer special opportunities for leadership, training, and discovery, thereby delivering good scientific returns on relatively small Canadian investments. Projects of this type may emerge out of phase with the Long Range Plan cycle. Funds need to be available to take advantage of new opportunities as they arise, and it is particularly important to continue support for those projects with international partnerships while they are scientifically competitive.

SCIENTIFIC RECOMMENDATION

Support strategic smaller-scale Canadian efforts giving breadth to the community. In particular it is important to continue supporting Canadian participation in the following international projects: ALPHA, JLab and offshore rare isotope beam experiments, and IceCube.

A number of major international facilities and experiments that will further the understanding of the universe will become operational in the coming years. It is important for Canada to engage in such projects to maintain vitality in the field. Furthermore, it is crucial to become active in early stages so that Canadians may take on leadership roles and to ensure success of the projects.

SCIENTIFIC RECOMMENDATION

Position Canada for key leadership roles in strategic projects and initiatives by supporting activities in potential future flagship endeavours. Those projects with significant Canadian participation should continue to receive support: ATLAS at the High-Luminosity LHC, Belle II, Hyper-Kamiokande, ILD at ILC, MOLLER and SoLID at JLab, nEXO at SNOLAB, and UCN/nEDM at TRIUMF.

Future progress in the field relies on improving existing technologies or developing new technologies to accelerate and detect particles. Canada should be active in developing these technologies, not only because they can improve ongoing projects and enable new experiments, but also because they can benefit and impact fields outside of subatomic physics and society as a whole.

SCIENTIFIC RECOMMENDATION

Support proposals for directed and generic accelerator and detector research and development for subatomic physics.

2. RECOMMENDATIONS: COMMUNITY OF SUBATOMIC PHYSICS RESEARCHERS IN CANADA

It is widely recognized that many science, technology, engineering, and math (STEM) fields, including subatomic physics, are generally characterized as lacking diversity. Many factors contribute to this imbalance, which spans from the student level to the most senior levels. Several committees have been put in place by the Canadian Association of Physicists, the American Physical Society, and the European Physical Society to identify the barriers, challenge the stereotypes, and promote actions to rectify the situation. The Canadian subatomic community should actively support such efforts to ensure and actively promote equal opportunities at all levels.

POLICY RECOMMENDATION

Canadian institutions, researchers, and funding agencies are encouraged to work together to foster a diverse physics community. All members of the Canadian physics community are encouraged to support the development and implementation of a coordinated strategic plan to achieve this, including compiling relevant information and statistics and monitoring progress. The community should actively promote balanced representation at all levels, including those with high responsibility and visibility, as individuals in high-level positions serve as important role models.

The subatomic physics community has the capacity to train more graduate students. These students either stay in the subatomic field as researchers or move on to contribute to many key areas of the Canadian economy or educational system. Given the small incremental costs associated with supporting additional graduate students, enhancing the existing funding channels specifically for the support of graduate student training would be a highly effective investment and of great value to Canada.

POLICY RECOMMENDATION

Increase funding for scholarships and the subatomic physics envelope to train larger numbers of graduate students. This will provide greater benefits to Canada by leveraging the community's capacity to involve more students in this area, training highly qualified personnel who can add value to society in a number of meaningful ways with skillsets relevant to many sectors, including academia, industry, and medicine.

3. RECOMMENDATIONS: RESOURCES AND SUPPORT FOR CANADIAN SUBATOMIC PHYSICS RESEARCH

The Canadian laboratories for subatomic physics are essential for the continued success of subatomic physics research in Canada. They provide the facilities to execute experiments at the laboratories and represent Canada's launchpads to the international network of laboratories in subatomic physics.

POLICY RECOMMENDATION

Continue strong support for the Canadian laboratories for subatomic physics: TRIUMF and SNOLAB.

The Institute of Particle Physics (IPP) Research Scientist program has been highly successful in raising Canada's international profile in particle physics and allowing Canadians to participate in the highest leadership positions in experiments at the forefront of particle physics. The particle physics community considers the IPP Research Scientist program to be its highest funding priority.

POLICY RECOMMENDATION

Ensure adequate funding of the existing strong IPP Research Scientist program.

CERN is arguably the world-leading laboratory for particle physics, with an enviable record for research, discovery, and international scientific collaboration. It is a model for productive and innovative partnerships with industry, providing a conduit for small- and medium-sized businesses to the European high-tech industrial sector. Canada can clearly benefit scientifically and economically from a more formal relationship with CERN, such as via bi-lateral agreements or by becoming an Associate Member. This could serve as a model for future partnerships with other international organizations and facilities.

POLICY RECOMMENDATION

Representatives of the government of Canada, funding agencies, other stakeholders at Canadian universities, institutes and laboratories, as well as industrial partners are urged to work towards a more formal relationship between Canada and CERN.

The NSERC subatomic physics envelope system is essential to provide long-term support for major national and international projects.

POLICY RECOMMENDATION

Retain the current envelope system used by NSERC for subatomic physics, including the functions of the Team Grant and Major Resources Support programs.

International approval for major projects can take years, with funding agencies in each nation involved. It is important that the sometimes long gap between CFI competitions does not prevent Canada from participating. By allowing applications for projects not yet approved, and making awards contingent on project approval, Canada can play an instrumental role in moving projects forward and effectively leveraging international funding.

POLICY RECOMMENDATION

Retain the capacity for CFI to consider applications for international projects not yet approved and provide awards contingent on the project approval.

Prior to moving forward on a new major project, assurances are needed that there will be sufficient capital, operating, and other resources available. Since support comes from independent organizations, it is important to coordinate the process by which a new project is approved.

POLICY RECOMMENDATION

Coordinate resources, funding, and approval processes across the agencies and laboratories that support subatomic physics in Canada.

Canadian participation in decision making for proposed major international facilities, such as the high-luminosity upgrade of the LHC and a future linear collider, requires coordination at a high level. This is a role not currently identified within Canadian government. Federal government involvement is required for discussions with representatives from other international governments and for securing special funding for Canadian components of such new international facilities.

POLICY RECOMMENDATION

Identify an office in Canadian government responsible for engaging with the international community in moving forward major new science initiatives.

The erosion of "opportunity funds" within the envelope threatens the community's ability to start new projects. To remedy this, an increase to the envelope is necessary and estimates of future recurring costs need to be taken into account when recommending funding levels for grants.

POLICY RECOMMENDATION

Carefully manage the NSERC subatomic physics envelope to allow for new projects to be developed.

Subatomic physics has been extraordinarily successful with the CFI program, which speaks to the excellence of this community in Canada. Operations funding through the NSERC subatomic physics envelope has not kept pace and is now limiting the ability of the Canadian community to retain its international standing in subatomic physics. In order for Canada to efficiently mature and amplify highly qualified personnel training and effectively engage in the ongoing and future program laid out in this report, the envelope will need to grow by $3M immediately and by an additional $4M over the next 5 years.

POLICY RECOMMENDATION

Grow the NSERC subatomic physics envelope by $7M over the next 5 years.

2. The Big Questions in Subatomic Physics

Feynman diagrams are used to express forces between subatomic particles.

A string of exciting discoveries in subatomic physics occurred in the last couple of decades. The Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator, began operations in 2009 at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The highlight of the first run of the LHC was the discovery of the Higgs particle in 2012, the first new elementary particle to be found since the top quark's discovery in 1995. This particle is the last missing piece of the Standard Model of particle physics (SM) — the framework that describes how subatomic particles interact through the electromagnetic, strong, and weak forces. It is also possible that the Higgs particle is the harbinger of a more fundamental theory of nature. The 2013 Nobel Prize in Physics was awarded to François Englert (Belgium) and Peter Higgs (UK), the theorists whose 1960s work was crucial to understanding the fundamental Higgs mechanism responsible for the masses of the elementary particles.

The LHC discovery of the Higgs is a crowning achievement of many years of subatomic physics research all over the world. The successful demonstration of the Higgs' existence is a triumph of scientific reasoning, which combined abstract theoretical deduction with increasingly complex experimentation. In the years to come, experiments both at the LHC and at future colliders will precisely measure the properties of the Higgs. The importance of these measurements cannot be overstated: while there are many reasons to believe that the SM is just an effective description, valid at sufficiently low energies, at the moment there is no experimental indication of the energy scale above which it breaks down. Precision measurements of the Higgs properties will help pinpoint the scale of new Beyond-the-Standard-Model (BSM) physics.

Dramatic progress was also made in revealing the nature of another fundamental building block of the Standard Model: the neutrinos. Near the turn of the millennium, experiments at the Sudbury Neutrino Observatory (SNO) in Canada and at Super-Kamiokande (Super-K) in Japan conclusively showed that different kinds of neutrinos can morph into each other. The existence of such processes, known as "neutrino oscillations," implies that neutrinos have mass. The 2015 Nobel Prize in Physics was awarded to Arthur McDonald (Canada) and Takaaki Kajita (Japan) for the discovery of neutrino oscillations and neutrino mass.

The fact that neutrinos are massive resolves outstanding puzzles that physicists have wrestled with for decades. At the same time, many important properties of neutrinos remain to be understood. Since neutrino mass cannot be fully accommodated in the SM, they constitute further evidence that the SM is not the final word. Measuring the many new parameters introduced by the nonzero neutrino mass, in ongoing and future experiments, will help in finding the suitable extension of the SM.

These two recent discoveries illustrate how experiments reveal answers to important questions in subatomic physics and at the same time raise even deeper questions. Addressing the big questions in subatomic physics is a truly global endeavour undertaken by a worldwide community performing experiments and developing theoretical models in close interaction. The experimental work is often conducted by large international teams working at complex facilities involving particle accelerators and sophisticated detectors, sometimes placed underground to minimize background from cosmic rays or other radiation. Theoretical breakthroughs may come from a moment of insight of one single person, but can also require massive calculations involving the most advanced computers and computing clusters.

The following sections review the main questions that remain unanswered and the ways researchers around the world are working to address them. The sections also highlight current activities of Canadian researchers at universities across Canada, at TRIUMF in Vancouver, at SNOLAB in Sudbury, and at the Perimeter Institute in Waterloo. These big questions serve as guideposts for the different research directions undertaken to improve the understanding of the universe at the smallest scales.

1 WHAT IS THE NATURE OF PHYSICS AT THE ELECTROWEAK SCALE AND BEYOND?

The Higgs particle represents a kind of matter never seen before. Its properties appear mysterious. For example, its mass is not constrained by any symmetry in the SM. Theories of BSM physics that explain these properties predict that the light Higgs is accompanied by an extended Higgs sector and/or other new particles near the TeV scale and beyond. There are many questions awaiting an answer: Is there a single Higgs or is it one of many? How does it couple to the other particles? Is the Higgs elementary or composite? Are there new particles near the electroweak scale? Are there extra sources of matter-antimatter asymmetry at the electroweak scale? Is the Higgs a portal to hidden dark particles in the universe?

Seeking the answers to these questions will continue during the second run of the LHC and after its upgrade to the High-Luminosity LHC (HL-LHC). A future e^+e^- linear collider such as the ILC proposed for Japan or CLIC in Europe would measure properties of the already observed Higgs particle even more precisely and possibly detect deviations due to new physics. These results will impact the current views of the fundamental theory and provide answers to the outstanding questions: What underlying principles determine the Higgs properties? Is the electroweak scale natural?

Precision experiments performed at lower energies provide another probe of new physics at or beyond the electroweak scale. By measuring electroweak processes with high precision, or processes forbidden in the SM, small effects arising due to new physics may be revealed. Examples arise in precision beta decay, parity-violating electron and neutrino scattering, atomic parity violation, and rare kaon and bottom hadron decays. All of these experimental programs use a precise understanding of the SM as a benchmark to which the experiment can be compared, and any significant deviation would signal new physics. A key requirement in this context is the need both for high-precision experiments and for increasingly accurate theoretical calculations of the SM predictions. In this way such experiments, in conjunction with theoretical calculations, can probe multi-TeV energy scales. The need for precision often means that the experiments must be conducted over long periods of time and with very intense particle beams.

A number of experiments are looking for sources of charge-conjugation and parity (CP) violation due to BSM physics, which is needed to explain the predominance of matter over antimatter in the universe. One strategy is to carefully study CP violation and search for deviations from the SM in the kaon and B-meson sector. Another is to search for electric dipole moments in a number of systems, ranging from the neutron to atoms and to molecules. Still another is to search for CP violation in neutrino oscillations with long-baseline experiments.

Other experiments seek to test the combined charge-conjugation, parity, and time reversal (CPT) symmetry, believed to be an exact symmetry of nature. A deviation would imply a breakdown of quantum field theory, and possibly a violation of Lorentz symmetry. Clock-comparison experiments and anti-hydrogen spectroscopy experiments probe CPT and Lorentz symmetry.

CANADIAN ROLES

Canada plays a leading role in ATLAS, one of the two large general purpose experiments at the CERN LHC. The ATLAS physics goals include probing the mechanism for electroweak symmetry breaking and searching for new physics at the TeV scale. ATLAS consists of approximately 3000 physicists (including 1000 students) from more than 177 universities and laboratories in 38 countries. The multi-institutional ATLAS-Canada team, founded in 1992 and now consisting of approximately 130 faculty members, postdoctoral fellows, and graduate students, had central roles in the discovery of the Higgs boson in 2012 and first exploration of its properties. Canadian leadership in ATLAS is well recognized in overall management roles such as the current deputy spokesperson of ATLAS and, in the past, publications committee chair, ATLAS collaboration board chair, and several other physics-group coordination roles. The ATLAS-Canada team is also playing a critical role in the instrumental upgrades of the experiment needed for the future running periods of the LHC, including construction of new muon detector elements for LHC Run-3, starting in 2021, and R&D related to new particle tracking chambers for HL-LHC, starting in 2026.

Canadian theorists have been very active in proposing ways in which the LHC experiments can test whether the newly discovered Higgs boson has properties that match the SM. Theorists also explore ideas such as supersymmetry, extra dimensions and composite Higgs models, any of which could be discovered in the upcoming LHC running periods. Canadian theorists also participate in international collaborations to address high priority issues such as the anomalous magnetic moment of the muon, where theory and experiment differ by 3 to 4 standard deviations. For comparison to an upcoming experiment at Fermilab, theorists in Canada have collaborated with the RBC-UKQCD lattice collaboration (based in the USA and UK) to provide definitive theoretical predictions.

ALPHA is a smaller scale international experiment at CERN with significant Canadian scientific leadership that aims to test CPT symmetry with anti-hydrogen spectroscopy and to test for possible differences in the gravitational interaction of matter and antimatter. The multi-institutional ALPHA-Canada team members have made critical contributions to the publications that have marked ALPHA's recent success. The ALPHA-Canada team was recognized with the 2013 NSERC John C. Polanyi Award for outstanding advances in science and engineering, highlighting their contributions to the instrumentation of ALPHA, the successful demonstration of anti-hydrogen trapping and subsequent trapping for 1000 seconds, and first measurements of anti-hydrogen spectroscopy. The new focus on measuring the gravitational interaction between antimatter and the Earth, called ALPHA-g, receives most of its financial support and much of its scientific leadership from Canada.

Belle II is an experiment in Japan at the frontier of precision measurements for flavour physics, with a particular focus on studies of bottom quarks, that could discover BSM physics. There are over 600 collaborators from 23 countries, including about 360 PhD physicists and 160 graduate students, with the Canadian team making up 3% of the PhD physicists and 6% of the graduate students. A Canadian is head of the Belle II institutional board, and the Canadian team is responsible for calorimeter calibration, GEANT simulation, and beam-background monitoring. Thanks to the development in Canada of cloud computing for Belle II, the Canadian team will be well positioned to lead analysis efforts on the data to be collected starting in 2017.

NA62 is an experiment at CERN designed to study charged kaons decaying in flight, which may provide a window into BSM physics. The Canadian group is playing an important role in the analysis of the NA62 data by bringing unique expertise acquired in previous experiments at TRIUMF and Brookhaven National Laboratory (BNL).

Studies of time reversal and CP violation are underway at TRIUMF through four complementary research programs, the neutron electron dipole measurement (nEDM), the radon and francium EDMS (RnEDM and FrEDM), and the ^{38m}K radiative decay program. The nEDM program is on track to make the world's best measurement of the neutron electric dipole moment. It is a Canada-Japan collaboration that began in 2009, where Canadians have a leading role in all major subsystems for both the UCN source and the nEDM experiment. For example, the proton beamline construction was completed in 2016 entirely by the Canadian group. The RnEDM program will take advantage of a predicted dramatic EDM enhancement (up to 1000-fold) due to nuclear octupole deformation, and the first step is the measurement of nuclear structure for several radon isotopes during the coming five years. The FrEDM program benefits from francium being comparatively easy to capture and cool, and also from having a strongly enhanced intrinsic electron EDM. The ^{38m}K radiative decay program at TRINAT will surpass current limits on time reversal violation at the MeV scale. Its sensitivity is enhanced by about two orders of magnitude relative to neutron decay.

The MOLLER experiment at JLab in the United States is sensitive to BSM physics at the TeV scale. It will access discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory by measuring the electron's weak charge and weak mixing angle through parity-violating electron-electron scattering. The Canadian group led the recent publication of the ground-breaking Compton polarimeter results. Canadians are also DOE level 2 managers for the spectrometer development and package leaders for the integrating detector package. MOLLER builds on the recent success of the Qweak experiment at JLab where Canadians have played a major role in determining the proton's weak charge. Detailed analysis of the full Qweak data set is nearing completion.

The Canadian-led FrPNC collaboration has established a francium trapping facility at ISAC (at TRIUMF). Atomic parity violation is sensitive to new physics, such as extra gauge bosons or leptoquarks, and the effect is enhanced in francium (18 times larger than in cesium). This research program will be enabled further by ARIEL's capability to deliver multiple beams simultaneously.

Several Canadian research groups have made important contributions to the determination of weak currents and the most precise value of the SM quark-mixing parameter V_{ud}. The 8π spectrometer, GRIFFIN, TITAN, and GPS facility at TRIUMF have recently produced high-precision measurements of several superallowed beta decays that further constrain weak scalar currents and provide a new benchmark for testing isospin symmetry breaking in nuclei. Moreover, the new GRIFFIN spectrometer is set to revolutionize measurements for $A \geq 62$. TRINAT (at TRIUMF) has performed the best measurement of β-neutrino correlation in the β decay of ^{38m}K to probe scalar interactions coupling to wrong-helicity neutrinos. The Canadian Penning Trap at Argonne National Laboratory (ANL) in the USA is studying β-neutrino correlations in ^{8}Li and ^{8}Be, with first results published and further improvements underway.

2 WHAT IS THE NATURE OF NEUTRINO MASSES?

While the existence of neutrino mass is now known, many questions about its nature remain unanswered: Are neutrino masses Dirac, Majorana, or a mixture of the two? What is the neutrino mass hierarchy? Is there CP violation in the neutrino sector? Is it related to the matter-antimatter asymmetry? Are there extra types of neutrinos not yet observed?

The possible Majorana nature of neutrino mass is probed by experiments looking for neutrinoless double-beta decay, which, if observed, would indicate that neutrinos are their own anti-particles. Neutrino oscillations will be studied using neutrinos produced by reactors, accelerators, and cosmic rays. These studies will shed light on the mass hierarchy, flavour mixing, and CP violation in the neutrino sector. The results of these experiments will impact the current views on the origin of matter-antimatter asymmetry as well as the role of neutrinos in the evolution of the universe. A coherent picture of how the neutrino properties fit into the quest for a fundamental theory should begin to appear.

CANADIAN ROLES

The Canadian researcher team in the EXO collaboration, which is searching for neutrinoless double-beta decay at the WIPP facility in New Mexico, has contributed calibration systems, radon control, process system design concepts, veto system mechanical construction, and materials testing through ultra-trace assays. They have been active in the data-taking and analysis process. Moreover, the first analysis coordinator, a current run coordinator, and the current chair of the collaboration board are Canadian researchers. The Canadian team is leading both the development of barium tagging, which has the potential to provide an exceptionally clean and sensitive probe of the neutrinoless decay in the upcoming nEXO project proposed for SNOLAB, as well as the development of silicon photomultipliers with unique wavelength, cryogenic, and low-radioactivity requirements.

The Canadian-led SNO+ experiment at SNOLAB will also search for neutrinoless double-beta decay and in addition aims to study low energy neutrinos produced in the Sun by the pep and CNO cycles. The Canadian groups within SNO+ have major responsibilities for detector components, such as calibration hardware, calibration sources, cover gas, hold-down rope-net, water systems, scintillator systems, and isotope purification and loading. SNO+ is complementary to EXO as the two experiments use different isotopes and different technologies.

The Canadian IceCube program near the South Pole, which began in 2010, has established specific expertise in the study of neutrinos at energies up to the PeV scale and has played a central role in many aspects of scientific analyses within the international collaboration. The Canadian groups provided the computing resources that led to the discovery of a diffuse high energy astrophysical neutrino flux, appearing as the cover story of *Science*, November 2013. One member of the Canadian team won the 2015 IUPAP Young Scientist Prize for Astroparticle Physics and another member is the collaboration's lead scientist for future upgrades in recognition of his role in leading the development of the proposed future low-energy extension called PINGU.

Canada is a founding member of the T2K collaboration in Japan, which is at the forefront of the world neutrino oscillation program. The critical concept of using an off-axis neutrino beam was initially proposed by a Canadian scientist, and its implementation at T2K was likewise spearheaded by a Canadian. The group was responsible for the design and construction of an optical transition radiation beam monitor that plays a critical role in the neutrino beam-line operation, as well as for the fine-grained scintillating detectors and time projection chambers that form the core of the T2K near detector. The Canadian group also provides Tier-1 storage for T2K data, at TRIUMF, and about half of the collaboration's computation resources. Canadian T2K members sit on the collaboration's executive board, and their other leadership positions include run coordinator, analysis coordinator, and publications committee chair.

3 WHAT IS THE NATURE OF DARK MATTER IN THE UNIVERSE?

A variety of cosmological observations suggest that the universe is composed of a large amount (27%) of invisible dark matter, while the visible matter makes up only 5% of the energy content (the rest is the so-called "dark energy"). Alternative theoretical efforts have proposed explanations involving defects in the topology of primordial quantum fields, gravity effects across multiple dimensions, and modifications to gravitational dynamics. Extensive effort has been devoted to BSM theories that include particles which could constitute dark matter. For example, dark matter could consist of weakly interacting massive particles (WIMPs) with fluxes of millions or billions per second traversing every square centimetre of the Earth, both on the surface and underground. A more recent realization, made within the past decade, is that there may exist lighter weakly coupled "hidden" or "dark" sectors. These may be accessible through accelerator and/or direct detection experiments. Furthermore, dark matter may also consist of axions, or even of new kinds of "sterile" neutrinos.

Subatomic physics can address a variety of questions about dark matter: Is the dark matter composed of particles that can be directly or indirectly observed? What are the interactions that determine the dark matter abundance in the universe? Is there a single type of dark matter particle or are there many? Do dark matter particles have significant interactions with the SM particles, leading to observable effects? How strongly do dark matter particles interact with each other?

Dark matter searches are based on direct and indirect detection of cosmic dark matter particles remaining from the Big Bang, as well as the detection of dark matter particles produced in colliders. Direct detection is the observation of dark matter particles scattering off atomic nuclei within a detector. To avoid background from known sources of scattering radiation, such as cosmic rays, detectors are placed in deep underground laboratories such as SNOLAB. Indirect detection is the observation of the products of cosmic dark matter particle annihilation taking place elsewhere in the universe. Finally, high energy colliders could produce dark matter particles that escape undetected, resulting in an excess of events with momentum imbalance. The lighter weakly coupled and hidden-sector kinds of dark matter could be detected at lower energy colliders through their effect on particle decay rates.

CANADIAN ROLES

Canada is involved in several direct dark matter search experiments, including DEAP, which is optimized for heavy WIMPS; PICO, which is optimized for spin-dependent interactions; SuperCDMS, which is optimized for light WIMPS; and VERITAS, which searches for dark matter annihilation within and beyond the Milky Way.

The DEAP collaboration is led by Canadian researchers and includes members from the UK and Mexico. The DEAP-3600 detector is presently being commissioned at SNOLAB. Scientists at Canadian institutions chair the groups responsible for low-level signal processing; calibration; pulse-shape discrimination; event reconstruction; the backgrounds group; run selection, data-quality and live-time; data-flow and software management.

The PICO collaboration spans 6 countries and Canadians represent more than 40% of the total membership. The modest scale of the PICO experiment, which is located at SNOLAB, allows Canadian students and postdocs to be heavily engaged in all aspects of the experiment, including design, construction, commissioning, operation, and analysis.

For SuperCDMS, Canadian contributions focus on two key aspects. One is the development of the data acquisition system at SNOLAB and its implementation for both the experiment itself and the different detector test facilities. The other is the testing and characterization of detectors and other cryogenic components. In 2014, a Canada Excellence Research Chair (CERC) was added to the membership of SuperCDMS, and research funding associated with this prestigious position is being used for a new test facility to be located underground at SNOLAB.

Canada continues to play a central role in VERITAS, a ground-based gamma-ray instrument operating at the Whipple Observatory in Arizona, USA. In addition to helping lead physics analyses, the Canadian group also supplied components to build the telescopes and has developed a number of devices to provide precise calibrations.

The ATLAS experiment at CERN is searching for direct production of dark matter from the interactions among SM particles. Belle II in Japan will also be sensitive to the direct production of new light particles, such as "dark photons" with non-zero mass, through precision measurements at lower energies.

Canadian particle theorists have been devoting a lot of attention to dark matter, both in terms of building dark matter models and predicting signals that dark matter could leave in different kinds of experiments. In various models, the dark matter is part of a sector containing very light states (the dark matter itself and/or some mediator) that couple very weakly to the SM. Generically, such very light particles would be difficult to detect at colliders, so other experimental techniques might be better suited for this task. Theorists have been actively exploring how these new light states could be detected at neutrino experiments, meson factories, and beam-dump or fixed-target experiments.

4 WHAT STRUCTURES UNDERLIE THE FORCES AND MATTER IN THE UNIVERSE?

The development of particle physics in the past 50 years has seen increasing unification of forces and symmetries. The Standard Model describes the unification of the weak and electromagnetic interactions, consistent with all observations, but it has various structures that beg for an explanation. For example, the fermions have different masses and come in two sectors, each with three families that mix with each other. In the quark sector, the masses are hierarchical and the mixing angles are typically small. In contrast, in the neutrino sector, some of the mixing angles are large and the hierarchy of masses is unknown. The question, asked in the 1930s by Rabi in connection with the discovery of the muon, "Who ordered that?", remains unanswered. A tantalizing idea, often driving efforts to explain these puzzling features, is that the electroweak interactions further unify, at higher energies, with the strong interactions into a "Grand Unified" theory. Considerable theoretical effort is also devoted to studying new models and mechanisms — some borrowing recent ideas from string theory — that attempt to explain the mass and mixing hierarchies and to find out how they could manifest themselves in experimental measurements.

Many theorists believe that a better understanding of quantum field theory might, in the long run, be useful in unraveling many of the puzzles of particle physics, e.g. the mass hierarchies. Current models of subatomic physics are specified by a quantum field theory Lagrangian. When couplings are small, computations can be performed in perturbation theory, using an expansion in powers of the weak coupling, but this does not apply for the strong interactions in the SM. In the absence of a small parameter, important questions arise: How do quantum field theories behave outside perturbation theory? Are there general properties and constraints on their possible nonperturbative behaviour? These questions are being pursued in a variety of ways; for example, using analytical tools, borrowed from string theory and supersymmetry, and via various dualities. When no analytical calculations are possible, the path integral can sometimes be computed numerically using lattice field theory, requiring major computational resources and international collaborations. Theoretical work continues to extend lattice field theory to incorporate fermions in chiral representations (like the SM) as well as supersymmetric theories.

A further gaping hole in the quest towards a fundamental description of nature demands an answer to the question: Can quantum mechanics and gravity be reconciled? It has been difficult to come up with a consistent theory of quantum gravity. String theory, due to the efforts by many theorists, has emerged as the best developed theory of quantum gravity. While there appear to be no direct experimental tests of the theory possible at this time, its mathematical consistency has led to many insights into both the nature of string theory itself and into difficult nonperturbative questions in quantum field theory. A topic that lies at the heart of the unification of quantum mechanics with gravity is the physics of black holes. One of the big successes of string theory was the 1990s computation of black hole entropy in terms of string micro-states. More recently, further progress in the understanding of black holes, in particular of the black hole information paradox, has been possible using gauge-gravity dualities. Known collectively as the AdS/CFT correspondence, these dualities, uncovered in the late 1990s, are theoretical equivalences between certain weakly coupled string theories on an anti-de Sitter space (AdS) and strongly coupled conformal field theories (CFT) in a lower number of dimensions. The AdS/CFT correspondence is the most important achievement in string theory of the past 20 years. Besides black hole physics, AdS/CFT is used to study hydrodynamics and to shed light on aspects of the theory of strong interactions (quantum chromo-dynamics, or QCD), especially on the properties of quark-gluon plasma and relativistic heavy-ion collisions.

Many ingredients and ideas of string theory have also been used to build TeV-scale models of BSM physics with novel properties. For example, extra dimensions have been argued to help address the hierarchy and flavour problems, while gauge-gravity duality has provided new qualitative tools to study composite Higgs models. String theory also contains many fields which are expected to be lighter than the string scale, such as axions and moduli. These fields can have consequences for cosmology, and string axions could even be searched for in tabletop experiments.

CANADIAN ROLES

Canada is home to a broad range of theorists working towards a deeper understanding of all aspects of subatomic physics. Some theorists keep a close connection to experimental observations and focus on the precision calculations crucial to experiments looking for tiny deviations from the SM. Others pay close attention to the searches for new physics at the LHC, studying models and their signatures, working in close collaboration with experimentalists.

A number of leading theorists focused on many aspects of string theory are based at the Perimeter Institute and at many Canadian universities. The AdS/CFT correspondence remains a very active topic of research, focused on its applied aspects as well as on attempts to better understand the physics underlying the gauge-gravity duality. An example of a topic where Canadian theorists and their international collaborators are leading the way is the study of the maximally supersymmetric Yang-Mills theory in four dimensions, dual to string theory in five-dimensional Ads space, which promises new insights into the nature of both quantum gravity and quantum field theory.

Members of Canada's subatomic theory community have won numerous research prizes, including several New Horizons Prizes of the Fundamental Physics Prize Foundation, the Gribov Medal of the European Physical Society, the Steacie Prize, the Herzberg Medal, institutional Killam Prizes, Canada Research Chairs, Fellowship in the Royal Society of Canada, and Fellowship in the American Physical Society.

The nature of theoretical research in subatomic physics allows for a lot of flexibility, and it is not uncommon for theorists to engage in research of both formal aspects of field and string theory and on phenomenologically relevant topics. While several of Canada's experimental programs have the potential to provide the crucial insight required for the next step forward in understanding the underlying forces and matter in the universe, it is difficult to anticipate any specifics. Continued support of a broad range of theoretical activities in subatomic physics will place Canada in a good position to capitalize on future breakthroughs, both in experiment and theory.

5 HOW DO QUARKS AND GLUONS GIVE RISE TO THE HADRONIC PROPERTIES AND THE PHASES OF HADRONIC MATTER?

The composite nature of nucleons, being made up of quarks and gluons, has been known for many years. There are partial answers from high-energy physics to questions such as how the quarks are distributed in the proton and how they move, and the 2004 Nobel Prize was awarded for the discovery of asymptotic freedom within the context of perturbative QCD. But QCD is still unsolved in the confinement regime, where the quark coupling strength is too large to allow perturbative methods to be used, and one of the central problems of modern physics remains the connection of the observed properties of the hadrons to the underlying theoretical framework provided by QCD. Solving this problem requires advances in both theory and experiment. Recent advances in lattice QCD, in combination with chiral perturbation theory, make it possible to extrapolate to physical quark masses, and thus allow direct comparison to experimental observables. Experiments are underway around the world to obtain a tomographic view of the quarks and their motion within the nucleon, to elucidate the role of gluons and gluon self-interactions in nucleons and nuclei, and to understand in detail how QCD governs the transitions of quarks and gluons into pions and nucleons.

At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons of nuclear matter may form a new state of matter that is colour-superconducting. Exotic nuclear matter can also be created by colliding nuclei at relativistic energies. In this case, "nuclear temperatures" can reach values that represent a state of matter (the quark-gluon plasma) as it existed during the first moments after the Big Bang. This is an active field of study at international facilities such as the Relativistic Heavy Ion Collider (RHIC) at BNL in the USA and the LHC at CERN. Theorists are also making significant contributions to the understanding of the phase diagram of nuclear matter. Their work has significant bearing on the quest to characterize the properties of the quark-gluon plasma and to the understanding of astrophysical phenomena such as neutron star structure and the evolution of the early universe.

CANADIAN ROLES

Canadian researchers are valued at nuclear physics laboratories worldwide, and their research provides foundational information about the basic building blocks of nuclear physics. This includes several studies of hadron form factors in Halls A and C at Jefferson Lab, several studies of proton and neutron polarizabilities at the Mainz Microtron, pion-nucleon physics at Oak Ridge National Lab, and photo-disintegration experiments at the Duke University free-electron laser facility. It is expected that these efforts will naturally evolve into research programs at experiments like SoLID and eventually the EIC.

The GlueX project at Jefferson Lab seeks to produce and classify exotic and non-exotic hybrid mesons through photo-production. Canadian involvement in GlueX began in 2000 and included the design and construction of the barrel calorimeter as well as R&D for photosensors.

A great deal of theoretical effort is devoted to calculate bound state masses and transition matrix elements from a variety of approaches. Notably, Canadians have been pursuing the use of potential models and of lattice QCD techniques to calculate these quantities for states involving heavy quarks. Recently, the LHCb collaboration announced the discovery of two baryons and referenced the work of Canadians who had earlier predicted the masses of those baryons using lattice QCD.

Canadian theorists are contributing to the understanding of the phase diagram of nuclear matter, providing insight into the exotic nuclear matter that existed during the first moments after the Big Bang. One of the achievements of the relativistic heavy-ion program at RHIC, which was confirmed at the LHC with ATLAS-Canada participation, is the success of relativistic fluid dynamics, as championed by theorists from Canada.

Canadian theorists recently performed the first *ab initio* calculations of nuclear structure corrections to the Lamb shift on muonic helium and muonic deuterium with a precision of 6% and 1%, respectively. This is crucial information for the ongoing puzzle of why measurements of the proton radius via Lamb shift spectroscopy on muonic hydrogen obtain a value which differs by 7σ from what was previously known from ordinary (electronic) hydrogen.

6 HOW DOES THE STRUCTURE OF NUCLEI EMERGE FROM NUCLEAR FORCES?

A central goal of nuclear physics is to explain the properties of nuclei and nuclear matter. This is a formidable task that is best approached in steps: from the basic equations of QCD, through to effective field theories, to inter-nucleon interactions and few-body systems, and further on to the many approaches used to describe nuclear structure, ranging from exact methods, such as Green's Function Monte Carlo, to the shell model and density functional theory. While calculations based on the nucleon-nucleon interaction have achieved quantitative success in reproducing the features of light nuclei, detailed agreement is still lacking for heavier nuclei. This is a problem that is common to the description of other complex systems, such as proteins. In nuclear physics, the development of a comprehensive, predictive theory of complex nuclei remains a key goal.

Worldwide, this goal has driven the recent development of high-quality radioactive beams of rare isotopes, as they allow a transition from a one-dimensional picture where the mass of a nucleus varies to a two-dimensional picture where both proton and neutron mass numbers vary over a wide range. With the recent completion of much needed detector infrastructure at TRIUMF's ISAC facility and securing of funds needed to complete ARIEL, Canadians have a unique window of opportunity to lead substantive advances in the field. Further work involves off-shore facilities such as the Canadian Penning Trap at ANL and significant contributions to experiments at the GSI Helmholtz Center for Heavy Ion Research in Germany and Jefferson Lab. Observations to date indicate striking anomalous behaviours in these rare isotopes, and the study of nuclei having a significant imbalance of neutrons and protons will provide the missing links to present understanding. These discovered phenomena and unexpected behaviour include the extended neutron radius of the so-called halo nuclei of helium and lithium and extra shell stability for neutron-rich calcium isotopes, at mass 54 or neutron number 34. Recent theoretical advances show strong promise to form a better linkage between the fundamental theory of strong interactions and the quantitative description of nuclear many-body phenomena. This includes new and exotic properties predicted and observed in radioactive nuclei and predicted for neutron stars.

CANADIAN ROLES

Studies of fundamental strong interactions in nuclei are carried out with significant leadership by the Canadian community making use of the most advanced experimental devices at TRIUMF, including TITAN, IRIS, TIGRESS, GRIFFIN and DESCANT. The capabilities of these experiments in combination with the unique secondary beam capabilities at ISAC, which has the world's highest intensity radioactive beams for many isotopes including the halo nucleus ^{11}Li, is putting Canadian researchers at the forefront of this field. The synergy among devices is exemplified in the way DESCANT can couple with TIGRESS to detect neutrons following fusion evaporation or with GRIFFIN to study β-delayed neutron emission.

Discovering new features in exotic nuclei such as in nuclear halos, finding unexpected signatures of changes in nuclear shell structure, and investigating the nuclear force and its impact on nuclear structure are topics where TRIUMF's ISAC facility together with the TRIUMF theory group are playing leading international roles.

At ISAC, Canadian led research teams have made important discoveries ranging from experiments using non-accelerated beams to re-accelerated beams. A few recent examples are masses of neutron-rich Ca and K isotopes measured at TITAN, which have confirmed theoretical predictions that include three-nucleon forces. These results spurred significant efforts in experiments worldwide (RIKEN, CERN, NSCL/MSU to name a few) and drove theoretical developments. Re-accelerated beam experiments at IRIS found new evidence of a long-sought new excitation mode, the soft dipole resonance in the halo nucleus ^{11}Li.

The collective properties of nucleons within a complex nucleus present a longstanding challenge in nuclear physics. Canadian research groups utilize the existing infrastructure for isotope beams and the experimental devices to study these phenomena, which are enhanced by novel isotope developments and by TRIUMF's flagship facility, ARIEL, which produces isotopes for physics and medicine.

Canadian researchers make strategic use of facilities beyond Canada's borders to complement the strong TRIUMF program. For example, the CPT spectrometer at ANL takes advantage of the different isotopes available from the CARIBU RIB facility. PREXII and CREX at JLab are expected to measure the neutron radii of ^{208}Pb and ^{48}Ca with high accuracy. Canadian researchers are leading programs of measuring radii of neutron-rich nuclei at the GSI-FAIR rare isotope beam facility. Exploring new shell evolution is another major program where Canadian researchers are playing lead roles and have made impactful new findings such as the unexpected doubly magic nucleus ^{24}O. Offshore programs are also led at other rare isotope beam facilities RIKEN-RIBF and NSCL-FRIB.

Canadian theorists at TRIUMF and at the universities are leading major initiatives to develop new many-body methods to describe structure and reaction properties of light-, medium-, and heavy-mass nuclei and play a major role in interpreting experimental data and guiding new experiments at TRIUMF and abroad.

7 HOW ARE THE ELEMENTS FORMED IN THE UNIVERSE?

Nucleosynthesis that occurred during the cooling following the Big Bang gave rise to primordial abundances of the lightest elements H, He, and Li. Nearly all other chemical elements in the universe are produced as a result of nuclear reactions in stars or cataclysmic events at the end of a star's life. The reaction products are expelled into the interstellar medium by stellar winds or events such as nova and supernova explosions, and neutron star mergers.

Central goals of nuclear astrophysics includes understanding the origin of the elements, the connection between the observed solar abundances and nuclear structure, the mechanism of core-collapse supernovae, the structure and cooling of neutron stars, and the equation of state for asymmetric nuclear matter. Nuclear astrophysics has benefited enormously from progress in astronomical observation and astronomical modelling, and a new era has opened with the use of radioactive isotope beam (RIB) facilities dedicated to the measurement of short-lived nuclides of astrophysical relevance. These include the determination of masses, half-lives, the structure of exotic nuclei, and the direct and indirect determination of the various cross sections involving radioactive nuclei. The nuclear astrophysics measurements at TRIUMF and other international RIB facilities form an integral part of their science programs. Much of the instrumentation employed is also used for nuclear structure research.

CANADIAN ROLES

In collaboration with theoretical nuclear astrophysicists, experimentalists use radioactive beams to investigate important aspects of nuclear astrophysics. At the ISAC facilities at TRIUMF, several experimental setups are focussed on the investigation of reactions and nuclear properties relevant for the nucleosynthesis of the chemical elements. There is a great need for more experimental data, in particular for heavy nuclei.

The DRAGON facility, a Canadian-led recoil separator with international partners, measures astrophysically important radiative (α and proton) capture cross sections. With a world-record beam suppression of one particle per 10^{14} incident ions, it has spectacular sensitivity. Of particular interest are the reactions that occur in explosive environments of novae, supernovae, and x-ray bursters. DRAGON's experimental reach extends to the high-mass region of $A \approx 80$.

The TUDA charged-particle scattering and reaction detector array is used by a collaboration of Canadians with the universities of Edinburgh and York in the UK. TUDA has, for example, enabled the extension of the ^{18}F (p, α) ^{15}O reaction studies into the astrophysically important energy regime of novae and has completed a high-profile measurement of the ^{26g}Al$(d,p)^{27}$Al transfer reaction to indirectly constrain the ^{26g}Al$(p,\gamma)^{27}$Si reaction.

The newly commissioned GRIFFIN spectrometer, in conjunction with the DESCANT neutron detector, is ideally suited for the investigation of very neutron-rich and short-lived nuclei. The upcoming experimental program will target β-delayed neutron emission probabilities and neutron spectra of key isotopes in the rapid neutron-capture process.

The TIGRESS γ-spectroscopy facility in combination with the SHARC particle detector can also be used for the measurement of astrophysically relevant transfer reactions. It is operated by an international team with Canadian leadership.

These TRIUMF experimental efforts are complemented by *ab initio* theoretical calculations of some of the investigated reactions important for astrophysics.

The Canadian Penning Trap is operated at the CARIBU facility at Argonne National Laboratory and has been extensively used to measure masses of neutron-rich nuclei produced in the fission of ^{252}Cf. Its counterpart at TRIUMF is the TITAN facility which complements the experimental studies by Canadians to understand the heavy element formation in the rapid neutron and proton capture processes.

The BRIKEN project is a large international collaboration that is merging ^{3}He-filled neutron counters from various existing setups into one world-leading high-efficiency setup at the RIKEN Nishina Center in Japan. In comparison to the program at TRIUMF with GRIFFIN and DESCANT, the focus of the BRIKEN project is the discovery and first-time measurement of more than a hundred exotic isotopes which can emit up to three neutrons after β-decay. The Canadian-led part of the experiments is focussing on the isotopes between ^{76}Co and ^{92}Se.

3. Canadian Subatomic Physics Research Plan

Researchers working at the DRAGON recoil separator at TRIUMF.

With its strong track record of research and training accomplishments, Canadian subatomic physics is poised to build on its achievements over the next five-year period. To do so, the recommended plan promotes a two-fold approach involving sound strategic investment in both Canada's theory community as well as a selected array of ongoing experimental efforts. To advance subatomic physics research further in the coming years, Canada must support strategic smaller-scale experiments while positioning itself for leadership in future major projects. Several projects are anticipated to undergo their approval processes during the 2017-2021 period, while some larger projects will have concurrent requests for Canadian facilities and resources. Adjustments to the plan may therefore be necessary over the course of the plan and will require judicious management of the NSERC subatomic physics funding envelope.

A number of the experimental endeavours in the 2017-2021 planning period will have lifetimes that extend into the 2022-2026 planning period. Likewise, major projects requiring significant expenditures during 2022-2026, will need strategic investments already in the current 2017-2021 five-year plan.

1. THEORY

Subatomic physics theorists drive and develop understanding of the big questions outlined in Chapter 2. Theory development is essential to answering these questions and to formulating the resulting future research directions. Many in this broad community, among them world leading scientists, are addressing these exciting questions by developing theoretical tools and models ranging from the formal to the phenomenological. The broad range of expertise allows the community to work quickly and efficiently on new directions as they are identified. In addition, experimental work benefits significantly from a strong theory community to help interpret results and suggest new paths for discovery. It is therefore essential that the subatomic theory community continues to receive strong support, which currently accounts for 15% of the NSERC subatomic physics envelope.

SCIENTIFIC RECOMMENDATION

Maintain strong support for research in theoretical subatomic physics.

2. ONGOING FLAGSHIP FACILITIES AND EXPERIMENTS

The Canadian subatomic physics community's track record of scientific success and its current strong position in research and development provide a clear impetus for continued investment in ongoing Canadian and international research projects in the next five years. To continue this success, it is essential to provide robust support for several ongoing flagship projects, all of which have solid backing from established Canadian researcher teams. These projects, which have grown through decades of planning and development, are now helping to discover answers to the big questions in the field and are attracting global attention to Canadian physics.

With ARIEL, the rare isotope program at TRIUMF will see a dramatic increase in productivity, both from the new types of beams (driven by the new electron accelerator) and from the tripling of the number of beamlines, which will also allow new longer-running experiments to take place. The high impact measurements enabled by these investments require a further ramping up of highly qualified personnel (HQP), starting in about 2018, to maximize the potential scientific output and most effectively utilize the capabilities of this new resource.

The flagship SNOLAB facility is hosting the DEAP-3600, PICO, SuperCDMS, and SNO+ experiments conducting searches for dark matter and neutrinoless double-beta decays. The complementary dark matter experiments DEAP-3600, PICO, and SuperCDMS (30 kg) have planned upgrades that, if funded, would commence construction late in the 2017-2021 period. Depending on the success of these experiments, there are plans to propose to upgrade DEAP-3600 to DEAP-50T (50 tonnes) and SuperCDMS to a 200 kg variant, at which point sensitivity to dark matter would be limited by neutrino interactions. Once filled with liquid scintillator, the SNO+ experiment will come online to commence several years of data-taking with a capability to conduct studies of tonne-scale double-beta decay, solar neutrinos, geo-neutrinos, and supernova neutrinos.

The CERN-based ATLAS experiment on the energy frontier enabled by the LHC will continue Run 2 data taking until the end of 2018. A subsequent two-year shutdown will see Phase-I upgrades made to the ATLAS detector, in preparation for the higher trigger rates anticipated in Run 3, expected to commence in 2021. During the Run 2 and Run 3 data taking periods, parallel efforts will be directed towards preparation for the Phase-II upgrades, to be implemented during the next five-year planning period. During this period, the ATLAS experiment will make significant advances in measuring properties of the known particles, such as the Higgs boson, and in searches for phenomena beyond the Standard Model, including dark matter. These advances will require the continuous support of the Canadian ATLAS Tier-1 computing centre.

The T2K accelerator-based neutrino-mixing experiment at J-PARC in Japan will continue to take data as it advances its program of searching for CP violation in the neutrino sector by making precise measurements of several parameters fundamental to neutrino and anti-neutrino oscillations. The larger data sample will help to address questions about the origin of neutrino masses and mixing parameters. In addition to the existing program, T2K collaborators in Canada are developing future directions via participation in the Hyper-Kamiokande project, a proposal to upgrade the Super-Kamiokande detector to a volume 25 times larger. Canadian T2K members are also leading the NuPRISM proposal, which would involve construction of a large water Cerenkov detector situated approximately 1 km from the neutrino beam source and having a capability to exploit variations in the neutrino energy spectrum.

SCIENTIFIC RECOMMENDATION

Provide continued support and resources to the following ongoing flagship facilities and experiments, now producing scientific results thanks to significant coordinated Canadian and international efforts and financial investments, to ensure that they fully realize their potential:

- TRIUMF radioactive beam facilities and associated experiments. The anticipated tripling of beam delivery with ARIEL over the next 5 years will significantly increase scientific output, training opportunities, and broader impacts.
- SNOLAB and its experiments, beginning their search for dark matter interactions and neutrinoless double-beta decay, phenomena never before observed.
- ATLAS experiment, now exploring proton collisions near the ultimate energy and with the increasing luminosity of the Large Hadron Collider.
- T2K experiment, studying neutrino properties with increasing precision as the neutrino beam intensity continues to ramp up.

3. STRATEGIC SMALLER-SCALE EXPERIMENTS

As the science develops and new opportunities and ideas arise, it is important to maintain a diverse program of excellence in subatomic physics research. The Canadian research program is grouped around several key questions, outlined in Chapter 2, that are each internationally recognized as being high priority. Appreciating the need to maintain scientific excellence and a critical mass of effort, the Canadian subatomic physics research community has taken leadership roles and is making other significant contributions to selected smaller-scale projects, both domestically and abroad. The many interconnections between these thematic scientific questions require advances in one area in order to progress in a complementary area. A broad and diverse program, with several strategic smaller-scale efforts, is therefore vital to the health of the field and should be maintained in all funding scenarios.

To accomplish such breadth, resources need to be available with lead times of under five years to support smaller efforts that are in early stages of research and development, that are ongoing, or that require limited resources. In all cases, the scientific excellence and significant potential for major scientific advances must be the minimal criteria for support. Several important projects will be taking data domestically in the 2017-2021 period, providing breadth to the program.

NEWS at SNOLAB utilizes 1.4 meter diameter ultra-pure copper spheres filled with a light gas as a drift and amplification volume to detect the ionization induced by nuclear recoil arising from the scattering of a dark matter WIMP. Operating at pressures up to 10 bar results in an active target mass of several kilograms.

HALO is a low-cost Canadian-led supernova neutrino detector that began full operation at SNOLAB in 2012. The detector consists of 80 tons of lead instrumented with 360 m of ^{3}He neutron counters shielded by 30 cm of water. An upgrade to HALO, to be sited at LNGS in Italy, is at the proposal state and, if approved, is expected to be

Scientist being lowered into the SNO+ acrylic vessel to prepare the detector for filling.

constructed and running by the end of the 2017-2021 planning period.

Other important experiments with Canadian involvement will also be run offshore. The ALPHA-Canada collaboration plans to operate its upgraded ALPHA-2 trap at CERN for precision antimatter spectroscopy while simultaneously performing precision antimatter gravity measurements using ALPHA-g. Also at CERN, the NA62 experiment will take data during the 2017-2021 period to inform analyses of rare kaon decays with branching fractions sensitive to new physics at high mass scales.

The $g-2$ experiment at J-PARC is proposing to measure the anomalous magnetic moment of the muon for comparison with the Standard Model expectation. The technique is complementary to that used in a past BNL (BNL E821) experiment, which found a 3.6σ discrepancy, and an upcoming Fermilab (E989) experiment. The first stages of construction and data-taking are slated to take place during the 2017-2021 planning period.

The JLab high-luminosity continuous-wave superconducting electron LINAC has recently undergone an upgrade from 6 GeV to 12 GeV maximum beam energy, opening up many new physics opportunities. Canadians have leadership roles in a variety of experiments measuring precision QCD, hadron form factors, and electroweak physics, including the GlueX and PREX/CREX experiments.

The rare isotope beams produced via projectile fragmentation at in-flight facilities such as GSI-FAIR, RIBF-RIKEN, and NSCL/FRIB have complementary capabilities for reaction studies compared to the low-energy-beam reaction spectroscopy program at TRIUMF. Canadians work at these facilities on a number of important measurements, including the determination of the neutron-skin thickness of exotic isotopes, studies of extremely neutron- rich and proton-rich nuclei, β-delayed neutron emission branching fractions and half-lives for very neutron-rich isotopes, studies of shell structures and nucleon distributions, X-ray spectroscopy of super-heavy elements, and studies of fission barrier heights in neutron-rich nuclei.

The Canadian built near detector tracker for the T2K neutrino experiment located in Japan.

The IceCube Neutrino Observatory, near the South Pole, will take data throughout the 2017-2021 period. The statistically limited high-energy neutrino flux studies, including spectral shape and flavour composition ratio, will undergo significant advancement and test for the presence of physics beyond the Standard Model. Canadians are taking a leading role in the development of the proposed future low-energy extension of IceCube, called PINGU.

SCIENTIFIC RECOMMENDATION

Support strategic smaller-scale Canadian efforts giving breadth to the community. In particular it is important to continue supporting Canadian participation in the following international projects: ALPHA, JLab and offshore rare isotope beam experiments, and IceCube.

4. FUTURE MAJOR PROJECTS

Leading participation in the development of major projects during the 2017-2021 period is needed for Canadians to continue to make significant contributions in advancing our understanding of the universe by incisively attacking the key questions of global importance to subatomic physics (Chapter 2). Canadian scientists are already supporting all of the projects discussed below; in some cases they are taking on leading roles. It is important to appreciate that, at the time of this writing, some of these projects, which may become the flagship projects of the next decade and beyond, have not yet received approval.

On the energy frontier, a major future high-luminosity upgrade to the LHC (HL-LHC) has been approved by CERN, and most of the ATLAS-Canada community, the largest concentration of Canadian physicists on a single experiment, will continue on the project. Work has already begun and will continue during this five-year period to define and commence execution of the anticipated ATLAS-Canada detector contributions to the Phase-II upgrades that will ready the ATLAS experiment for HL-LHC operations. In addition to the detector upgrades, the Canadian ATLAS Tier-1 computing centre will need a significantly scaled-up capacity boost, and an important contribution to the upgrade of the HL-LHC accelerator system will be expected to take place through TRIUMF.

Belle II and UCN/nEDM are two essential and approved projects at the precision frontier that indirectly probe well above the TeV scale in a manner complementary to ATLAS. Both have teams of Canadian researchers who commit significant fractions of their research time to their respective projects. Belle II will examine fundamental symmetries and the dark sector, after commencing data collection during this period. Considerable investments in infrastructure at TRIUMF for UCN/nEDM have already been made, and it is essential that the facility and the nEDM experiment operate during this period in order to take full advantage of those investments. Phase 1 of the UCN project, comprising the neutron source itself and a test nEDM apparatus, is nearing completion. In Phase 2, the nEDM experiment itself and source upgrades will lead to full exploitation of the new facility.

The double-beta decay EXO-200 detector, currently operating at the WIPP facility, will continue to acquire data during this period, and upgraded electronics, background control, and analysis improvements will provide a threefold improvement in sensitivity. Research and development is underway to prepare for an upgrade, named nEXO, from 200 kg to 5 tonnes with continued Canadian leadership. The Canadian EXO community is driving the development of new advanced detection techniques for application in the future nEXO detector. Should the 5-tonne nEXO program succeed technically and receive approval in the United States, the intention is to locate it in SNOLAB, with construction occurring during this five-year planning period.

The International Linear Collider (ILC) is a future precision frontier project that, if funded, would likely attract a large number of Canadian researchers and would require significant resources for a Canadian contribution. Through the technology transfer enabled by the instrumentation choices made for ARIEL at TRIUMF, the Canadian industrial sector is well positioned to contribute to aspects of the ILC accelerator program. The current small team of Canadian physicists working on the International Large Detector (ILD) should be supported in order to maintain a stake in this important project and its broad scientific program, for which a funding decision is expected early in the five-year period.

The MOLLER experiment, followed two years later by the proposed larger-acceptance SoLID detector at Jefferson Lab, is also in the design phase and, if it moves successfully through the US approval process, will see its Canadian participation grow.

Future neutrino experiments, focussed on the mass hierarchy and CP violation, already have Canadians working on them. These experiments, which are not yet funded, are Hyper-Kamiokande and T2K/NuPRISM in Japan and PINGU in IceCube at the South Pole. Decisions on funding for these projects are expected in the early part of the planning period. The outcome of Japan's plans in particular will have a marked effect on how both the Canadian neutrino and ILC communities will concentrate their research interests in the coming decade.

SCIENTIFIC RECOMMENDATION

Position Canada for key leadership roles in strategic projects and initiatives by supporting activities in potential future flagship endeavours. Those projects with significant Canadian participation should continue to receive support: ATLAS at the High-Luminosity LHC, Belle II, Hyper-Kamiokande, ILD at ILC, MOLLER and SoLID at JLab, nEXO at SNOLAB, and UCN/nEDM at TRIUMF.

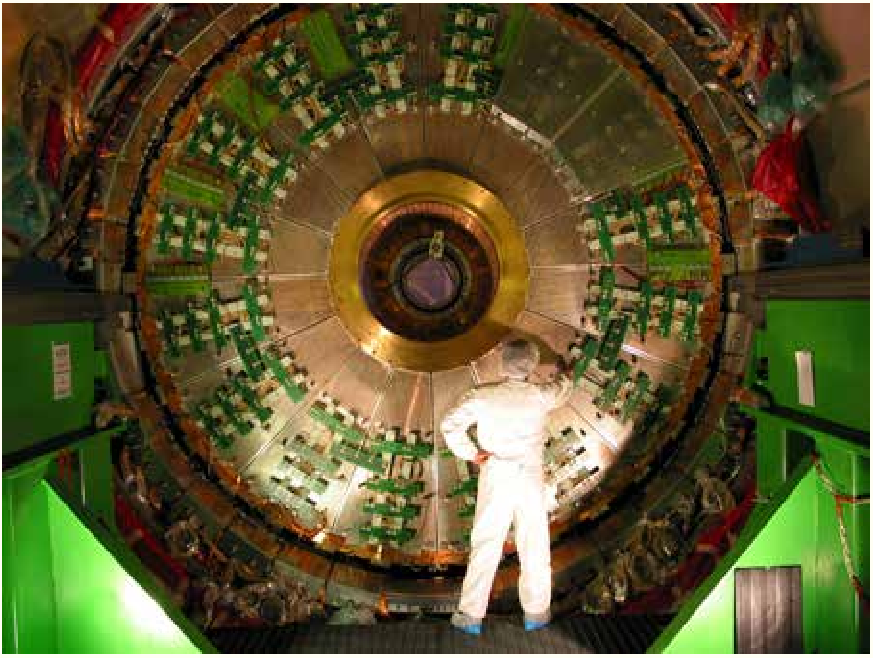
5. LOOKING AHEAD TO 2022-2026

The longer view ahead will depend not only on a set of critical major international funding decisions occurring during the 2017-2021 period, but also on the successes of the earlier experiments and theory at pulling further back the curtain that lies between humankind and the secrets of the subatomic world. Further insights into the Higgs boson, with possible new particle companions to the Higgs, may have been uncovered at the electroweak scale. Dark matter or hints of a sector of dark or supersymmetric particles may have emerged. Unexpected behaviours in the neutrino families, relating perhaps to their flavour-changing or particle-antiparticle characteristics, may also have been shown to exist. Inherent to the subatomic research community's approaches to the discipline is an enduring preparedness and agility to detect unexpected new phenomena. This sentiment is embodied in the designs of the current — and currently planned — experimental apparatus such that new discoveries, of global scientific and potential societal and economic impact, could readily occur at various stages of Canada's prominent participation in the worldwide subatomic physics program.

Several major experimental initiatives, promising to substantially improve current knowledge of the universe from a subatomic-physics perspective, will begin their design and development phases in the 2017-2021 period, but will require significant capital allocation in the 2022-2026 period. In even the best available funding scenarios, the allocation of Canada's resources to larger subatomic physics experiments is optimized by coalescing on single world-leading projects for any particular approach. Beginning in the 2017-2021 period, and converging at points in the 2022-2026 period, the Canadian community will need to direct efforts towards single major experiments probing the mass hierarchy and CP nature of neutrinos, studying neutrinoless double-beta decay, and searching directly for dark matter. Each of these efforts will require considerable resources overall, and it is therefore essential that substantial contributions come from foreign partners, including for those projects sited in Canada.

Researchers in the worldwide subatomic physics community are advancing designs of several large proposed facilities that could have implications for future Canadian research directions and efforts. For high-energy particle physics applications, an important goal is the development of high-gradient acceleration technologies, using either conventional superconducting cavities or other techniques such as plasma wakefield acceleration. The next generation of energy-frontier machine is expected to be either a linear electron-positron collider or a circular collider with a circumference possibly as large as 100 km.

Fermilab, the premier US particle physics and accelerator laboratory, has embarked on increasingly international efforts, both in neutrino science using particle accelerators and in the development of future particle colliders. An internationally designed, coordinated, and funded program for



The Canadian built Hadronic Endcap Calorimeter for the ATLAS experiment at CERN.

a Long-Baseline Neutrino Facility (LBNF) has been proposed to be hosted at Fermilab, with a worldwide neutrino collaboration developing the Deep Underground Neutrino Experiment (DUNE).

Internationally, there has also been much activity towards the construction of an Electron-Ion Collider (EIC) in the US in the coming decade. Canadian nuclear physicists are taking roles in the planning and prototyping for this new facility, the scientific case for which has been favourably reviewed. Next-generation extensions to the ISAC facility are also being considered, involving a possible construction of an ion storage ring receiving further accelerated beams from ISAC-II. This could enable experiments to be performed with very neutron-rich light nuclei, beyond the reach of future in-flight facilities like FRIB.

Opportunities such as these require ongoing investments in directed and generic detector and accelerator research and development to assure the continued excellence of Canadian subatomic physics in the coming decades and to sustain the positive impacts that fundamental research has made on Canadian society and industry. In order to achieve this, it is essential to ensure that an appropriate fraction of Canadian subatomic physics funding be available year-to-year in support of detector and accelerator research and development. Not only does the future of the field depend on it, but it also provides outstanding training of highly qualified personnel with skills that are directly transferable to the industrial sector.

SCIENTIFIC RECOMMENDATION

Support proposals for directed and generic accelerator and detector research and development for subatomic physics.

4. Community of Subatomic Physics Researchers in Canada

Student working with helium compressor at TRIUMF.

Subatomic physics research is spread across Canada. Teams and individual researchers work at 31 universities and at TRIUMF, SNOLAB, and the Perimeter Institute, as illustrated in Figure 1. The following presents a profile of the Canadian community of subatomic physics grant-eligible researchers and their research activities. The data come from NSERC databases and from a community survey of NSERC-eligible grant holders, undertaken by the Long Range Plan Committee in November 2015. The response rate to the survey was over 70% and roughly balanced across the sub-disciplines.

1. COMMUNITY PROFILE

In 2015, there were 233 subatomic physics researchers across Canada who received research support through NSERC as a principal or co-applicant. For this sample, the average number of years since completion of their BSc and PhD degrees is 31 and 25 years, respectively. Of those reporting their degree institutions, about 60% completed their BSc in Canada while about 60% completed their PhD outside Canada. One third of those with a BSc from Canada completed their PhD outside of Canada. These data indicate that a large fraction of the community has an international background.

Overall, only 12% of the sample of 233 are women, similar to the fraction of female researchers in the NSERC Physics Evaluation Group, 13%. The gender imbalance in subatomic physics is reducing, but slowly. For the 62 people in this sample who received their PhD degree in the past 15 years, 23% are female. Other diversity information was not available to the committee.

Canadian society is inherently diverse. The celebration of this diversity is important to its societal and cultural identity. Equitable representation and promotion of opportunities are important for the health of the Canadian economy and for scientific research and education. It is widely recognized that many science, technology, engineering, and math (STEM) fields, including subatomic physics, are generally characterized as lacking diversity. Many factors contribute to this imbalance, which spans from the student level to the most senior levels. Several committees have been put in place by the Canadian Association of Physicists, the American Physical Society, and the European Physical Society to identify the barriers, challenge the stereotypes, and promote actions that foster a truly diverse and inclusive community. The Canadian subatomic community should actively support such efforts to actively promote and ensure equal opportunities and an inclusive culture at all levels.

POLICY RECOMMENDATION

Canadian institutions, researchers, and funding agencies are encouraged to work together to foster a diverse physics community. All members of the Canadian physics community are encouraged to support the development and implementation of a coordinated strategic plan to achieve this, including compiling relevant information and statistics and monitoring progress. The community should actively promote balanced representation at all levels, including those with high responsibility and visibility, as individuals in high-level positions serve as important role models.

Diversity can be increased, albeit slowly, through "renewal," defined here as people retiring and new researchers being hired. Between 2010 and 2015, the community grew from 224 to 233. Roughly 13% of the 2010 community retired (or resigned) and stopped receiving research support from NSERC by 2015. This loss was balanced by an equal number of new hires over the same period. Furthermore, the renewal was roughly balanced for each region of Canada, as shown in Table I. The small net growth of 4% results from those who were NSERC-eligible throughout the period. There were more who started than who stopped receiving support after 2010.

The 13% renewal rate over a period of five years is consistent with a steady retirement rate for careers lasting roughly 35 years. The community survey included questions about activities in five years' time. Overall, the projected renewal rate for the coming five years was 13%, but there was a significant difference between theorists (6% stopping research) and experimentalists (17% stopping research).

The full community of researchers involved in subatomic physics goes well beyond those eligible for NSERC grants. Undergraduates, graduates, and postdoctoral fellows all make valuable contributions to the discipline. The community survey asked NSERC-eligible grant holders (i) to indicate how many graduate students they currently supervise, and (ii) to estimate how many they would supervise if access to graduate student funding were not a factor. The survey results show that, on average, they supervise 2.1 graduate students but they have the capacity to supervise about 80% more. This response was uniform across subdisciplines.

Students trained in subatomic physics either stay in the field as researchers or move on to contribute to many key areas of the Canadian economy or educational system. Given the small incremental costs associated with supporting additional graduate students, enhancing the existing funding channels specifically for the support of graduate student training would be a highly effective investment and of great value to Canada.

POLICY RECOMMENDATION

Increase funding for scholarships and the subatomic physics envelope to train larger numbers of graduate students. This will provide greater benefits to Canada by leveraging the community's capacity to involve more students in this area, training highly qualified personnel who can add value to society in a number of meaningful ways with skillsets relevant to many sectors, including academia, industry, and medicine.

FIGURE 1

The 31 universities and TRIUMF, SNOLAB, and Perimeter Institute participating in subatomic physics reach across the nation. Alphabetically they are Acadia, Alberta, Brandon, British Columbia, Calgary, Carleton, Concordia, Fraser Valley, Guelph, Grenfell Campus of Memorial, Laurentian, Laval, Lethbridge, Manitoba, McGill, McMaster, Montréal, Mount Allison (MTA), Northern British Columbia, Perimeter (PI), Quebec à Montréal, Queen's, Regina, Saskatchewan, Simon Fraser, SNOLAB, Saint Mary's, Toronto, TRIUMF, Victoria, Waterloo, Western, Winnipeg, and York.

Region	Departures	New Hires
BC	8	8
Prairies	5	5
Ontario	10	12
Quebec	6	3
Atlantic	0	1
Total	**29**	**29**

TABLE I
Renewal of NSERC-eligible positions in subatomic physics between 2010 and 2015, broken down by region.

2. RESEARCH PROFILE

Chapter 2 describes how subatomic physicists in Canada are active in answering all of the big questions in the field. To quantify how the community spreads its effort across the sub-disciplines, the Long Range Plan Committee matched each NSERC grant to the main question it was addressing, except for the more general grants that support accelerator research or the Major Resource Support (MRS) program. This was done for two years, 2010 and 2015, to see how redirection of effort and renewal has changed the community research profile over that five year period. Table II shows the number of NSERC applicants and co-applicants supported by grants broken down into the major categories of theory, experiment, accelerator research, and further broken down by the big question that is the main focus of each grant. The inner columns of the table show how the community changed, either through redirection of effort (those starting or stopping research or changing research areas) or through renewal (new hires or retirements).

The data show that renewal and redirection over a five year period can have a significant effect on the makeup of the community. This argues for flexibility within the NSERC SAP funding envelope to accommodate changes in community priorities and to allow promising new research directions to be pursued. The larger changes during this period are a reduction in theoretical community working on Questions 5-7, and growth in the experimental community working on Questions 1-3 and 6. The drop in the experimental community working on Question 5 is primarily due to the end of support for the completed ZEUS experiment. None of the theory grants are connected primarily to Question 2 (neutrino mass), as the frameworks for neutrino oscillation and neutrinoless double-beta decay are already well established. Likewise, there is no experimental activity connected specifically to Question 4 (structures), as this is primarily a theoretical endeavor that builds upon existing experimental results. However, as has been the case in the past, it may provide the theoretical foundation to experiments in the near or distant future.

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

Chapters 2 and 3 emphasize the important role that theoretical work plays in interpreting experimental results and defining new directions for exploration. Table II, however, shows disproportionately small theoretical activity on Questions 6 and 7, in the areas of nuclear structure and nuclear astrophysics, for which there is enormous Canadian investment and experimental activity at TRIUMF. Increased activity in non-perturbative aspects of subatomic physics would benefit these and other experimental areas with significant Canadian effort. For example, improved modelling of neutrino interactions for oscillation experiments and more precise calculations of matrix elements for neutrinoless double beta decay experiments would reduce important uncertainties in these measurements. Advances in computing technology, combined with new methods, are leading to progress in dealing with non-perturbative problems and provide a great opportunity for growth in this area.

The simplified analysis described above indicates that the community is dynamic. The field, however, cannot be compartmentalized into a few independent research streams, as people’s efforts and projects are generally directed towards more than one stream. To explore the connections between research areas, the community survey collected information on how researchers split their efforts. As expected, very few indicated that they split their effort between theory and experiment: more than 90% of the theory full-time equivalent (FTE) comes from people who work on theory exclusively. Theorists were asked to specify to which of the big questions their current theoretical research was related (either directly or indirectly). Figure 2 graphically shows the interconnection of theoretical work by indicating the number of responses connecting pairs of questions.

Many in the experimental community divide their time across multiple projects that address different questions. Experimentalists were asked in the survey to report the fraction of time they devote to each of their activities. The question format did not allow the results to be broken down by the big questions. Instead, the efforts were grouped according to projects within the Canadian Institute of Nuclear Physics (CINP) and according to general categories within the Institute of Particle Physics (IPP). The interconnections within CINP and IPP research are shown in Figure 3.

The division of research time depends strongly on the area of research. For example, it is more typical for those working at the energy frontier to devote most of their time to that area (average FTE/person is 0.86), while those working to detect dark matter typically work on other areas (average FTE/person is 0.4).

			redirection		renewal		
		2010	**in**	**out**	**new hire**	**depart**	**2015**
Theory		**71**	**2**	**9**	**12**	**12**	**64**
Q1	Beyond SM	17	5	2	3	2	21
Q2	Neutrino mass	0	0	0	0	0	0
Q3	Dark Matter	4	1	2	3	0	6
Q4	Structures	26	3	5	3	4	23
Q5	QCD and hadrons	17	1	6	1	3	10
Q6	Nuclear structure	6	0	2	2	3	3
Q7	Element formation	1	0	0	0	0	1
Experiment		**146**	**19**	**5**	**16**	**16**	**160**
Q1	Beyond SM	80	18	7	7	9	89
Q2	Neutrino mass	38	4	5	6	1	42
Q3	Dark Matter	20	3	0	4	0	27
Q4	Structures	0	0	0	0	0	0
Q5	QCD and hadrons	10	0	5	0	0	5
Q6	Nuclear structure	30	8	4	4	4	34
Q7	Element formation	16	0	2	1	2	13
Accelerator		***6***	***9***	***1***	***1***	***1***	***14***
All categories		**224**	**21**	**2**	**29**	**29**	**233**

TABLE II

Number of applicants and co-applicants on NSERC grants in 2010 and 2015 broken down by major categories and by the big question addressed, defined in Chapter 2. For this study, each grant was matched to the main question it was addressing. The inner columns indicate changes resulting from redirection and renewal for each category. Redirection in (out) refers to those who were NSERC-eligible for both years but started (stopped) being supported on a grant in the category. New hires were appointed after 2010 and the depart column includes retirements and resignations prior to 2015.

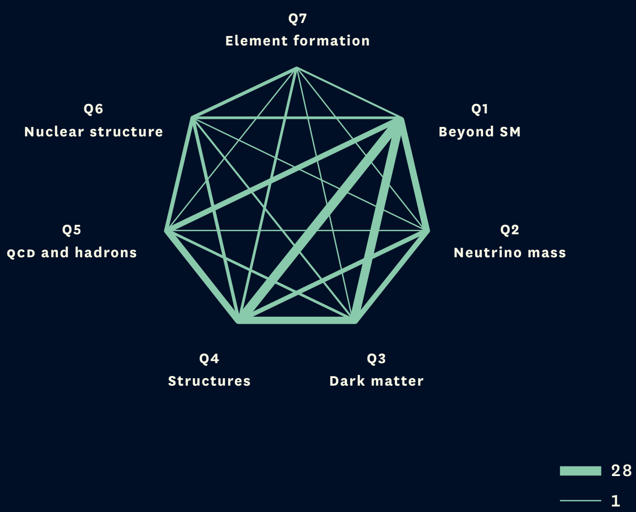


FIGURE 2
This figure demonstrates the interconnection of theoretical research. The width of the line connecting two questions is proportional to the number of theorists indicating that their work was related to both questions. The legend at lower right shows the scale for the line widths, in this case ranging from 1 to 28 theorists.

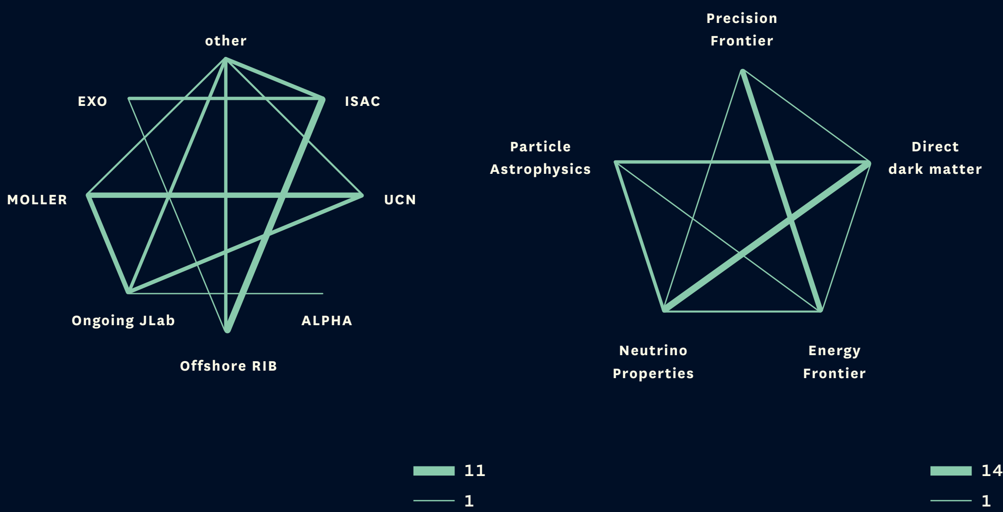


FIGURE 3
These figures demonstrate the interconnections of experimental research across different projects within CINP (left) and across different categories within IPP (right). The width of the line connecting two areas is proportional to the number of experimentalists indicating that they work on both areas. The legends show the scales for the line widths.

5. Resources and Support for Canadian Subatomic Physics Research

Meson Hall experimental area at TRIUMF.

The Canadian subatomic physics community is supported in its activities by three major laboratories/institutes, which offer unique experimental infrastructure or support for theoretical research. These three organizations are the TRIUMF laboratory for nuclear and particle physics and accelerator-based science in Vancouver, the SNOLAB facility for underground science in Sudbury, and the Perimeter Institute for Theoretical Physics in Waterloo. These research centers are complemented by two "virtual" institutes, representing nuclear and particle physics: the Canadian Institute for Nuclear Physics and the Institute of Particle Physics, respectively. Details on these important research organizations are provided in this chapter.

Across the country, degree-granting universities of all sizes are the engines driving the majority of formalized HQP training in Canadian subatomic physics. Much of the nation's theoretical research, as well as outreach to undergraduates and the public, takes place in the university system. This chapter discusses these aspects and the extensive networks of university-based resources that are key to the successes of Canadian subatomic physics research.

Many Canadian subatomic physicists also utilize facilities and institutions abroad and work within international collaborations. This provides special opportunities for exchange of ideas and to mount world-leading experiments to advance the field. This chapter briefly describes some of the facilities outside Canada where Canadian subatomic physicists meet the world.

The chapter concludes with a description of the funding sources that makes subatomic physics research possible in Canada. The field has been extraordinarily successful with capital funding through the CFI program which speaks to the excellence of this research community. Operations funding through the NSERC subatomic physics envelope has not kept pace and now threatens continued success of the discipline in Canada.

1. CANADIAN LABORATORIES AND INSTITUTES

Having delivered nearly five decades of discovery, TRIUMF has a vibrant reputation globally as Canada's national lab for particle and nuclear physics and accelerator-based science.

It hosts its own successful domestic physics program and supports Canada's participation in subatomic physics on the international stage. It is owned and operated by a university consortium of 19 Canadian institutions and represents a combined capital investment of over a billion dollars. Its unique research capabilities attract national and international users for nuclear and particle physics experiments as well as for theoretical studies. TRIUMF hosts and supports a number of workshops and conferences every year. In particular, the theory workshop program has been very successful in bringing to Canada major international experts in the field of nuclear theory and particle phenomenology. This is essential to foster collaboration between theorists and experimenters at the international level. In addition, TRIUMF supports a Summer Institute (TSI), which brings together graduate students in subatomic physics. TRIUMF also hires about 70 summer and co-op students from across Canada and abroad every year, introducing undergraduates to worldclass subatomic physics research in Canada.

TRIUMF is home to a major accelerator facility, which uses circular and linear accelerators to produce and deliver secondary particle beams (isotopes, mesons, and neutrons). This accelerator complex is key to the Canadian domestic program in subatomic physics, which includes nuclear physics and astrophysics, as well as smaller-scale particle physics programs. The field of low-energy nuclear physics and astrophysics relies on unique and specialized accelerator infrastructure including production and primary beam driver facilities, as well as methods to select the secondary beam, synthesize short-lived isotopes, and deliver them to the experimental stations. TRIUMF's ISAC facility is North America's regional ISOL facility and represents one of the leading RIB infrastructures in the world. With almost three decades of experience in the production and delivery of secondary isotope beams, TRIUMF attracts the global experts in the community to carry out leading-edge experiments. The ARIEL accelerator and isotopes project, an approximately $100-million CFI and multi-provincial investment, represents a flagship program in Canada. ARIEL will include novel and additional production features, access to new isotopes, and will surpass current yield limits for many neutron-rich isotopes. This will ensure that Canada will stay at the top of the global endeavor to answer pressing questions in nuclear physics and astrophysics and attract the best researchers worldwide.

TRIUMF also enables significant construction and testing capabilities of large-scale detector components for off-shore or underground applications such as at SNOLAB. TRIUMF's accelerator expertise is recognized for its contributions to major projects, such as the LHC and the J-PARC neutrino beam. This expertise has been leveraged by the Canadian SAP community to contribute components to major experiments in Europe and Asia utilizing TRIUMF's unique specialized expertise in detector R&D, electronics and mechanical design, and fabrication. The specialized skills of the people as well as the modern infrastructure are key to not only participate, but also lead in global efforts in nuclear and particle physics.

The SNOLAB facility is one of the leading underground science facilities in the world, and was home to the SNO experiment, which earned the Canadian Arthur McDonald his Nobel Prize in 2015. Its unique feature is a major experimental environment at a depth of approximately 2 km below ground, which provides ideal research conditions for nuclear and particle physics rare-event experiments, matched with excellent auxiliary above-ground infrastructure. SNOLAB represents a world-unique infrastructure due to the environment it provides to the user science community. This comes about from the underground and laboratory structure and the expert support systems available. SNOLAB attracts the global community in underground science to carry out cutting-edge and award-winning science.

SNOLAB operates excellent development facilities for underground detectors, including purification systems for liquids, such as liquid detectors or shielding materials. Of paramount importance for underground studies is the control of materials used in the experimental equipment, as impurities contribute to the detected background and, if not treated carefully, would render the massive shielding from the underground environment useless. SNOLAB has developed selection technologies and standards that benefit the community engaged in underground studies at SNOLAB as well as for experiments around the world.

POLICY RECOMMENDATION

Continue strong support for the Canadian laboratories for subatomic physics: TRIUMF and SNOLAB.

The Perimeter Institute for Theoretical Physics (PI) is a unique, independent research institute devoted to foundational issues in theoretical physics, including subfields of subatomic physics. Since its establishment in 2001, PI has attracted to Canada some of the world's leading researchers in string and particle theory. PI also has a significant impact on the Canadian particle physics community, guiding and supporting the experimental efforts through research carried out by local faculty or associate faculty at Canadian universities.

PI acts as one of the hubs for theoretical physics research in Canada. Such an institution is very valuable not only to stimulate interactions between the various physics sub-fields, but also to connect theory and experiment. PI regularly hosts topical workshops on current themes in particle theory. In partnership with the University of Waterloo, PI also organizes the Perimeter Scholars International (PSI) program, an intensive one-year Master's program in theoretical physics. In addition, many of Canada's subatomic physics theorists are affiliate members of PI, which gives them the opportunity to regularly visit and spend time in this stimulating international environment. Perimeter, SNOLAB, and TRIUMF jointly organize TRISEP, a tri-institute summer school on elementary particles.

The CINP supports the promotion of nuclear physics and its researchers and plays a vital role in the self-organization of the Canadian nuclear physics community. The IPP fulfills this role for the particle physics community. Both institutes contribute significantly to the long-range planning process, which helps consolidate the subatomic physics community effort in Canada. Moreover, through its NSERC grant, the IPP supports eight particle physics research scientists, who often play significant and key roles in the major high-priority projects and experiments with Canadian participation. These scientists can devote the majority of their time to a dedicated effort and thereby help structure the Canadian contributions to maximize the overall impact. The particle physics community considers the IPP Research Scientist program to be its highest funding priority.

POLICY RECOMMENDATION

Ensure adequate funding of the existing strong IPP Research Scientist program.

The combination and complementarity of these institutes and laboratories enable both experimental and theoretical Canadian world class research in the field of subatomic physics. The tremendous impact and success that the five institutes for subatomic physics have had on science in Canada is not only due to the infrastructure and support built up over many years, but also due to the flexibility and dynamics of the laboratories and institutes. There is direct feedback from the community with regards to changing and developing needs and requirements. This is typically captured by formal mechanisms through user groups or user representations. At TRIUMF, the users are represented through the TRIUMF User-group Executive Committee, which provides formal feedback to the ongoing operation and science exploitation. TUEC is also involved in the formal future planning exercise that TRIUMF carries out every funding cycle with its Five-Year Plan. The dynamic adaptation of TRIUMF includes the installation of the new ARIEL facility to provide not only more and different isotopes to the national and international users, but also novel

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

particle detector development and fabrication capabilities. At SNOLAB, the national and international community is represented in the SNOLAB Experiments Forum, a formal body within the management structure of SNOLAB, which provides feedback on operational and development needs. The user community participates in the SNOLAB strategic plan and provides guidance on novel developments needed to maintain leadership position in underground science.

2. FACILITIES ACROSS CANADA

Across Canada, facilities at degree-granting academic institutions are complementary to and crucially linked with the national and international institutes and laboratories dedicated to subatomic physics research. These institutions, indicated in Figure 1 in Chapter 4, typically champion subatomic themes in their strategic research planning and range from the large medical-doctoral research universities, to medium-sized comprehensive institutions, and to smaller universities with primarily undergraduate programs. The Canadian university system is a fertile enabler of world-leading research output, not only by virtue of the academic models used to train graduate and undergraduate students, but also through the significant aggregate facility resources made available to researchers. Universities are hosts to a majority of the nation's community of theoretical subatomic physicists and accordingly are nodes for much of the field's Canadian HQP training and outreach to undergraduates and the public. Subatomic physics resources that are located in or near these facilities bring with them not only myriad practical advantages in light of Canada's expansive geography, but also significant engagement with the general public and local industry distributed at different points within the country.

In addition to the provision of valuable laboratory and office spaces, the success of many Canadian subatomic physics researchers relies

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

on university departmental or shared resources, including electronics development and fabrication support, machining facilities and personnel, engineers, laboratory technicians, and local computing and networking systems. The university-subsidized personnel and equipment capabilities are in many cases nationally unique and can be informally shared between researchers at different institutions but typically in the same experimental or theory collaborations.

The CINP and IPP help optimize use of nationwide resources through their scientific councils. The IPP Research Scientists are affiliated with universities but have greater agility than regular faculty to liaise between universities and laboratories in Canada and abroad. PI, SNOLAB, and TRIUMF have direct university faculty connections through adjunct, joint, and bridging appointments.

More formal sharing of university-based resources takes place through the NSERC-funded Major Resources Support (MRS) program. Specialized subatomic physics MRS facilities have been operating at the University of Alberta, Carleton University, the Université de Montréal, Queen’s University, and the University of Victoria. These facilities are available to support, for example, detector development work by providing engineering design, hardware fabrication and installation, electronics design and support, and data acquisition and simulation expertise. The resources at these facilities are available to the entire Canadian subatomic physics community by way of proposal applications submitted for consideration by resource allocation boards.

Of critical importance to the Canadian subatomic physics community are the significant resources for the high-performance computing that is essential to reconstruct and analyze data, produce simulated data samples, and perform theoretical calculations. Compute Canada is an organization formed by the research community across Canada and is funded by CFI and corresponding provincial sources. One of the ten globally distributed ATLAS Tier-1 sites is operated and managed by ATLAS-Canada and located in Vancouver (initially at TRIUMF but now moving to Simon Fraser University). The

Tier-1 operation cannot be discontinued during LHC Run-2, so the facilities at TRIUMF will remain available over the transition period. TRIUMF will remain involved in Tier-1 operations, though a service-level agreement is being established with Compute Canada. The ATLAS-Canada collaboration also runs its Tier-2 supercomputing centres at university-consortia facilities operating at McGill, SFU, Toronto, and Victoria using primarily Compute Canada resources. These resources address the large-scale, CPU-intensive computing needs related to data analysis and the generation of simulated events. Many universities also support local computing clusters, designed to satisfy the day-to-day research computing needs of individuals at their institutes. HEPnet/Canada administers NSERC-supported planning, oversight, and facilitation of the national and international networking for the country's subatomic physics community, provided through CANARIE. This includes linking the Canadian ATLAS Tier-2 sites with researchers at the universities or with the ATLAS Tier-1 computing centre at TRIUMF.

3. INTERNATIONAL LABORATORIES AND INSTITUTES

Science has played a vital role in unifying Europe, demonstrating its capacity as a tool for peace and cooperation with the establishment of many fruitful scientific collaborations that traverse national boundaries. A clear example of this is the existence of the CERN laboratory located on the French-Swiss border near Geneva. It is an international organisation at the forefront of fundamental research in nuclear and particle physics, and it currently hosts approximately 11,000 users from 100 states world wide. CERN was founded by 12 European countries in 1954. These countries became the founding members of the CERN Council, the body that steers the development of particle physics in Europe, now represented by 21 member states. This council structure has been a key element to the success of subatomic physics research in Europe, enabling long-term planning and commitments to projects. As an example, the proton-proton Large Hadron Collider at CERN took more than two decades from inception to operation, requiring the coordination of the efforts of over 10,000 engineers and scientists to build and operate the LHC and its detectors. It is interesting to see that this CERN-inspired international approach to collaborative science is now being applied elsewhere, with the aspirations of Fermilab in the United States to embark on the LBNF/DUNE project as an international project from the outset.

Since its inception, CERN has played a leading role in establishing the foundations of the Standard Model of particle physics. It directly detected the mediators of the fundamental weak force (W and Z bosons) in 1983, brought in the 1990s the knowledge of the fundamental electroweak force to a new level of precision with the LEP collider, and finally it discovered the Higgs boson in 2012 with the LHC. This work has brought international recognition to the CERN Laboratory. As a by-product of CERN's contributions to fundamental physics, it has also become a hotbed of technological innovation in areas of cancer therapy, medical and industrial imaging, radiation processing, electronics, measuring instruments, new manufacturing processes and materials, and information technology, and it is also the birthplace of the World Wide Web.

Given the depth and breadth of its scientific program, CERN is arguably the leading laboratory for particle physics in the world, with an enviable record for research discovery and international scientific collaboration. It is a model for productive and innovative partnerships with industry, providing a conduit for small- and medium-sized businesses to the European high-tech industrial sector. CERN also is a training ground for the next generation of science researchers and innovators, providing them with the knowledge and opportunities to launch their careers in industry and academia.

Canada has been contributing significantly to experiments based at CERN for many decades but as a country has no formal relationship with CERN.

Past participation of Canadian scientists at CERN has been through in-kind contributions to the individual experiments in which Canadians have been involved (a memorandum of understanding with the ATLAS experiment exists) and in the LHC accelerator facilities (TRIUMF made significant in-kind contributions to the construction of the LHC as a lead-up to Canada's involvement in ATLAS and has a cooperative agreement with CERN, currently under renegotiation). This Canadian investment in the CERN scientific program has in large part enabled Canada's CERN-based research enterprise: in 2013, it was estimated that approximately 70 Canadian faculty members, 30 postdoctoral fellows, and 80 graduate students were involved in CERN's experimental and theoretical physics programs.

As CERN embarks on its future program, which includes projects of high scientific interest to Canadians (such as ATLAS with the high-luminosity LHC, ALPHA-g, the rare kaon decay experiment NA62, accelerator R&D, future radioactive ion projects, and continued theoretical collaborations), the present time is an important opportunity for Canada to formalise its scientific footprint in international science with official ties to CERN. This could be achieved, for example, via bi-lateral agreements or by becoming an Associate Member of CERN. Associate Membership would allow Canada to attend the CERN Council and committee meetings, giving it a seat at this international decision-making table. It would give Canadian industry access to the $300-400 million in CERN contracts awarded annually and to CERN's business incubation centres, which proactively target new and emerging companies with commercialisation of CERN technological developments. Such membership would also give Canadians access to scientific positions open to associate members and training and development of technical and scientific skills for students and early career researchers. The cost of Associate Membership is approximately 10% of a full membership, which for a country like Canada would likely amount to a cost of approximately $10 million annually. Such funds cannot be allocated from within the existing NSERC SAP funding envelope and would have to be identified from other governmental sources.

POLICY RECOMMENDATION

Representatives of the government of Canada, funding agencies, other stakeholders at Canadian universities, institutes and laboratories, as well as industrial partners are urged to work towards a more formal relationship between Canada and CERN.

With the capability to deliver variable energy electron beams between 1-12 GeV of unprecedented quality and stability, JLab is one of the world's leading nuclear physics user facilities, numbering nearly 1,400 users. Several groups of Canadian experimentalists and theorists perform research there, making it the largest center for offshore Canadian nuclear physics research. Canadians are the third largest international group at JLab, behind France and Italy.

The JLab high-luminosity continuous-wave superconducting electron LINAC has just been upgraded from 6 GeV to 12 GeV maximum beam energy, opening up many new physics opportunities whose merit has been rated very high by a wide variety of scientific reviews. Canadians have leadership roles in a variety of experiments measuring precision QCD, hadron form factors, and electroweak physics, including the GlueX, PREX/CREX, Qweak, and MOLLER experiments.

Over the past decade, there has been a significant effort by Canadians to contribute to new hardware in Halls A, C, and D, and this equipment is either already in the process of being commissioned with beam or will be expected to in the next 1-2 years. Canadian contributions to the JLab 6 GeV program have shown themselves to be of very high impact, and this leadership has been even more visible in the highest priority parts of JLab's 12 GeV program. Investments in the scientific program of JLab have proven to be very effective, providing access to unique world-leading facilities not available in Canada.

TRIUMF main control room.

The High Energy Accelerator Research Organization (KEK) in Japan was established in 1997 after a reorganisation of several institutes and laboratories, including the National Laboratory for High Energy Physics (also called KEK, established in 1971). KEK provides the particle accelerators and other infrastructure needed for research in high-energy physics, material, life science, and other related areas of science in Japan. It has recently received acclaim for its contributions to the elucidation of neutrino oscillations; it hosted the facilities related to the 2015 Nobel Prize in Physics and the 2016 Breakthrough Prize in Fundamental Physics. It has two campuses: the KEK laboratory (in Tsukuba) and the J-PARC facility (in Tokai).

The KEK laboratory, which currently has approximately 900 employees, has hosted several experiments over the years, some with significant international cooperation. Its recently completed scientific achievements include the long baseline neutrino experiment, K2K, measuring neutrino oscillations (program completed in 2004) and the Belle experiment using the KEKB (*B*-hadron factory) e^+e^- storage ring (ended in 2010). An upgrade to the SuperKEKB/Belle II experiment was approved in 2010 and will ramp up to a fully operating experiment within this five-year plan. The KEK facility also hopes to host the ILC, an e^+e^- accelerator effort involving approximately 300 universities/laboratories worldwide.

The J-PARC facility is a joint project between KEK and the Japan Atomic Energy Agency. The high-energy proton accelerator facility, whose construction was completed in 2009, is a multidisciplinary laboratory whose applications include research in fundamental nuclear and particle physics, material and life sciences, and nuclear technology. In particular, the main 50 GeV energy proton ring is used to create the neutrino beams directed to the Super-Kamiokande facility 300 km to the west, used by the long-baseline T2K experiment.

In recent years, Canada has contributed significantly to KEK's neutrino physics program, becoming a key member of the T2K experiment as well as contributing to the neutrino beamline and remote handling of the neutrino target. Canada is now ramping up an important collaborative effort in *B*-hadron physics on the Belle II experiment after having acquired the expertise in *B*-hadron physics at the BaBar experiment at the SLAC facility in the United States. Canadian physicists at BaBar can proudly claim to have contributed to the 2008 Nobel Prize in Physics by providing the experimental confirmation of the predictions regarding the nature of the weak interaction and matter-antimatter asymmetry. In addition, a small team of Canadian physicists has an ongoing R&D involvement for the ILC, in preparation for a decision of the future of this program. The TRIUMF laboratory and KEK have a memorandum of understanding on cooperation in projects of mutual interest that covers "academic exchanges and joint research," including research in support of T2K, LHC, materials and molecular science, study of fundamental symmetries in particle physics, the Belle II experiment, rare isotope science, and the UCN facility at TRIUMF where KEK has recently made investments. TRIUMF and KEK have also recently established mutual branch offices in each other's laboratories: at KEK to support Canadian researchers at KEK and J-PARC and at TRIUMF to support KEK and other Japanese researchers in their activities at TRIUMF.

Canadians access international facilities all over the world, even at the South Pole Station, Antarctica. The Amundsen-Scott station provides excellent infrastructure for the scientific activities at the South Pole, including the IceCube facility, the world's first cubic-km-scale neutrino detector. The IceCube facility laboratory houses the power distribution, communications and data acquisition systems for the complete detector, which currently comprises the primary array, designed to detect the highest energy neutrinos, and two smaller subarrays, IceTop, and DeepCore, the low-energy extension of IceCube, that have strongly enhanced the physics reach.

The recent successful detection of high energy neutrinos of astrophysical origin by IceCube, as well as measurements of neutrino oscillations and searches for dark matter with DeepCore, has led the IceCube Collaboration to investigate possible extensions of IceCube with improved performance at both high and low energy. At high energy, an expanded detector in the deep ice and an improved surface array for identifying the air showers that produce atmospheric neutrinos are under consideration. At low energy, PINGU is designed as an integral component of IceCube, extending its scientific program to lower energies but using the same fundamental techniques and equipment as the high-energy extensions. Canadian researchers have established visible leadership roles in a broad range of both the high- and low-energy research activities of the facility.

The Canadian contributions at some of the facilities listed below may be smaller but they nonetheless have significant impact within their respective collaborations. These are often complementary efforts that will provide breadth and diversity to nuclear research in Canada as well as international visibility and the fostering of collaborations.

The rare isotope beams produced via projectile fragmentation at in-flight facilities such as the GSI Helmholtz Centre for Heavy Ion Research GSI-FAIR (Germany) and Radioactive Ion Beam Facility RIBF-RIKEN (Japan) have complementary capabilities for reaction studies compared to the ISOL production method at ISAC. A Canadian researcher is spokesperson of several experiments making use of the fragment separator at GSI. GSI is currently embarking on a major expansion of its facilities, and the Canadian investigator is coordinator of the continuation of these experiments within the SuperFRS Collaboration. Current and future experiments at RIKEN with participation and leadership from Canadian researchers include studies of both extremely neutron-rich and proton-rich nuclei with the EURICA γ ray spectrometer; the β-delayed neutrons at RIKEN project, which will begin operation in 2016; studies of shell structures and nucleon distributions; in-beam X-ray spectroscopy of super-heavy elements as a new technique to tag the production

Researchers working on the DESCANT neutron detector array at TRIUMF.

of super-heavy elements; and the study of fission barrier heights in neutron-rich nuclei.

The Canadian Penning Trap mass spectrometer has been operational at the Argonne National Laboratory since 2001. These studies are also complementary to those at ISAC. At present, CPT operates on the low-energy beamline of CARIBU, giving access to rare heavy ions not previously available for study. In the next 1-2 years, the CPT is planned to be moved to a new location where accelerated, high-energy, high intensity beams will be available.

The Mainz Microtron delivers electron beams up to 1.6 GeV energy. Along with a polarized tagged photon beam, frozen-spin target, and large acceptance detectors, the MAMI-A2 facility has unique access to high-precision measurements of nucleon structure. During 2009-2014, as the JLab experimental program was curtailed during 12 GeV upgrade construction, the Canadian research efforts at the Mainz facility grew. However, the MAMI accelerator complex will likely wind down operations over the next 5-7 years in favour of other opportunities. This dovetails well with the Canadian investigator plans, which are to complete the transition of most of their efforts back to JLab by the end of the decade. Some Canadians are also involved in fundamental neutron studies using the Spallation Neutron Source at the Oak Ridge National Laboratory, though this work is expected to gradually ramp down by 2022, as further efforts are also diverted to JLab. The Canadian work at the Duke University Free-Electron Laser Facility relies on HIGS, a Compton back scattering γ ray source producing photons between 2 and 100 MeV with either circular or linear polarization. Here, there has been a considerable investment of Canadian infrastructure from the former Saskatchewan Accelerator Laboratory.

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

4. CANADIAN FUNDING CHANNELS

Subatomic physics research in Canada is made possible primarily by financial support through the federal government, provincial governments, private organizations, and philanthropy.

Salaries for grant-eligible researchers are paid by their home universities, laboratories, or institutes. While universities operate with support from the provincial governments, there are also special federal programs to support exceptional researchers such as the Canada Research Chairs Program and the Canada First Research Excellence Fund.

To undertake research programs in subatomic physics, researchers apply to NSERC for individual discovery grants, team grants, and project grants. These grants support term-limited personnel (students and postdocs) and direct costs of research, such as travel and maintenance of equipment. While NSERC and some provinces offer graduate student scholarships, these are held by only a small fraction of graduate students in subatomic physics. The Research Tools and Instruments (RTI) Program allows researchers to purchase research equipment in support of one or more projects. In addition, the NSERC Major Resources Support (MRS) program supports major and unique human and technical resources made available for subatomic physics researchers across Canada.

Since the 1990s, funds for the suite of NSERC grant programs available to the subatomic physics community were combined into an overall envelope and allocated by one committee, unlike current practice for the other science and engineering disciplines supported by NSERC. A single evaluation committee for the subatomic physics envelope matches the special needs of subatomic physics, having a number of large collaborative projects with long time scales and international commitments. However, with projects spanning the country, the increasingly strict interpretations within NSERC of conflict of interest guidelines has resulted in Canadians being a minority of committee members, and thus the community has a diminished role in defining its own future endeavours. The total envelope funding has been constant over the past decade, roughly $23M, and currently represents 2.0% of the total NSERC funding for science and engineering.

Within the envelope, there are programs which are no longer available to the other disciplines supported by NSERC. The MRS program allows for efficient sharing of unique resources amongst subatomic groups across Canada, and it is important to retain this capability. In 2016, the Team Grant program was discontinued inside the subatomic physics envelope. This program allowed groups to pursue a thematic approach rather than a single project approach, but there were only two active grants in 2015. Given the low use of the program, and the flexibility of other programs within the envelope, it was determined that all of the activities supported through Team Grants could be supported by Individual or Project Grants.

POLICY RECOMMENDATION

Retain the current envelope system used by NSERC for subatomic physics, including the functions of the Team Grant and Major Resources Support programs.

In 1997, the federal government created the Canada Foundation for Innovation (CFI) to invest in state-of-the-art facilities and equipment for research and technology development. Funding competitions are undertaken on an irregular schedule, typically at two to three year intervals, depending on the injection of funds by the federal government. The major CFI programs generally support large scale capital investments, typically above $1M, and require matching, typically 40% from CFI, 40% from provincial sources, and 20% from other sources. Over the past 15 years, CFI contributions directly to subatomic physics have been substantial, at over $180M ($480M when including the matching amounts), and represent 4.0% of all CFI investments over that period. These amounts include major funding for ARIEL at TRIUMF, the SNOLAB facility and operations, and Perimeter Institute, totaling more than $120M ($300M with matching). In addition, subatomic physics benefits from computing resources coordinated through Compute Canada, which is funded through CFI.

International approval for major projects can take years with funding agencies in each nation involved. It is important that the sometimes long gap between CFI competitions does not prevent Canada from participating. By allowing applications for projects not yet approved, and making awards contingent on project approval, Canada can play an instrumental role in moving projects forward and effectively leveraging international funding.

POLICY RECOMMENDATION

Retain the capacity for CFI to consider applications for international projects not yet approved and provide awards contingent on the project approval.

At present, TRIUMF receives base funding in five-year allocations approved by the federal government and administered through a contribution agreement with the National Research Council. For the five year period beginning in 2015, the base budget is $267M. TRIUMF applies for supplemental funding through special federal programs.

SNOLAB currently receives funding through a combination of provincial and federal sources, including the CFI Major Science Initiatives (MSI) program intended specifically for the operation and maintenance of very large facilities. The annual operating budget is roughly $16M including in-kind support from Vale.

Perimeter Institute is a public-private partnership, currently funded by the Government of Canada ($10M annually), the Province of Ontario ($10M annually), and roughly matched by private philanthropy. Perimeter also applies for special federal and provincial programs.

The Canadian Institute for Nuclear Physics and the Institute of Particle Physics receive funding through NSERC MRS grants and institutional membership dues.

4.1 COORDINATING SUPPORT FOR SUBATOMIC PHYSICS

To efficiently use financial support and resources from several independent organizations, decisions to proceed with major new projects need to be coordinated. For example, capital funds for a

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

new project (for example, provided through CFI) should only be awarded if corresponding operation funding from other sources is assured (for example, provided through NSERC) and sufficient laboratory resources are available (for example, TRIUMF). Discussions between representatives of NSERC, CFI, TRIUMF, and SNOLAB are underway to improve such coordination. The upcoming CFI competition requires confirmation from the host facility that a project is approved prior to submitting the notification of intent.

POLICY RECOMMENDATION

Coordinate resources, funding, and approval processes across the agencies and laboratories that support subatomic physics in Canada.

Canadian participation in decision making for proposed major international facilities, such as the high-luminosity upgrade of the LHC and a future linear collider, requires coordination at a high level. This is a role not currently identified within Canadian government. Federal government involvement is required for discussions with representatives from other international governments and for securing special funding for Canadian components of such new international facilities.

POLICY RECOMMENDATION

Identify an office in Canada responsible for engaging with the international community in moving forward major new science initiatives.

4.2 INCREASING NSERC FUNDING FOR SUBATOMIC PHYSICS

Funding of the NSERC subatomic physics envelope has been roughly constant over the past decade, ignoring inflation, and is now insufficient to maintain Canadian leadership in this field. This section presents the case for additional investment on the basis of (i) restoring adequate operational support for ongoing research activities given the significant CFI investments, (ii) ramping up the next flagship experiments, (iii) restoring “opportunity funds” for starting new initiatives, and (iv) increasing support for graduate student training.

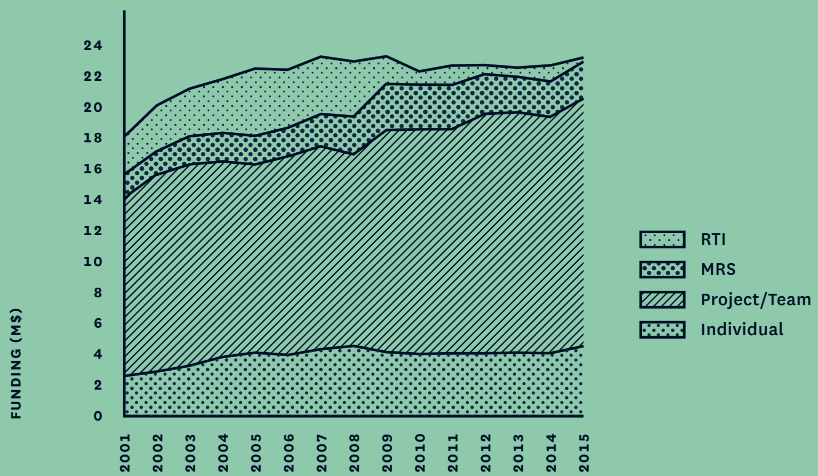


FIGURE 4

NSERC funding allocated to different grant programs within the subatomic physics envelope over the past 15 years. The share of funds towards recurring operation costs (Individual, Project/Team, and MRS) have seen a steady increase. The portion allocated to Research Tools and Instruments (RTI) has reduced as CFI has become the major source of capital funding.

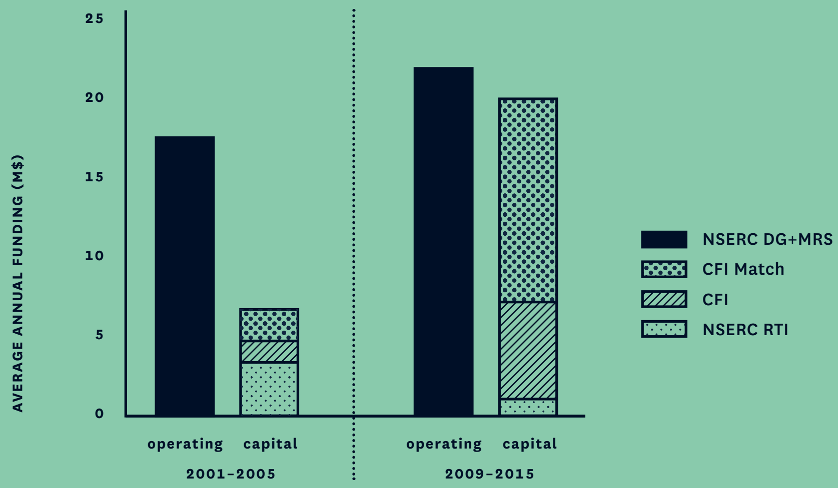


FIGURE 5
Average annual operations and capital funding (M$) for the period 2001-2005 compared with the period 2009-2015. The major CFI awards for ARIEL, the SNOLAB facility and operations, and Perimeter Institute are not included in these amounts. Operations funding (Discovery Grants and MRS) has not kept pace with the substantial growth in capital investments (RTI+CFI).

	2017	2021
Ongoing research activities	2	2
Ramping up next flagship projects	0	2
New opportunity funding	1	1
Graduate student training	0	2
Total increase	**3**	**7**

TABLE III
Recommended increase (in millions of dollars) to the subatomic physics envelope at the beginning and by the end of the period of this research plan. Following an immediate increase of $3M, the envelope should grow linearly by an additional $4M over the period.

(i) Ongoing research activities

The inception of CFI has allowed growth in Canadian subatomic physics research activity, during a period with constant NSERC envelope funding. With the movement of non-recurring capital expenditures out of the envelope, the division of the NSERC subatomic physics envelope to the various programs has changed dramatically. As shown in Figure 4, funding of recurring costs (individual, project/team, MRS) has grown over the past 15 years, while nearly eliminating support for the Research Tools and Instruments Grants Program (RTI).

Subatomic physics has been extraordinarily successful with the CFI program. While CFI competitions are designed for 30% success, 64% of subatomic physics applications in the 2009-2015 period were successful and 80% of the overall requested funding from this community was awarded. Over the past 15 years, subatomic physics has received 4.0% of CFI funding, while its share of NSERC funding has been fixed roughly at 2.0%, corresponding to less than 1% of tri-council funding. The great success with CFI speaks to the excellence of subatomic physics research in Canada.

CFI capital investments in subatomic physics have allowed the community to proceed with several important research endeavours that otherwise would not have been possible. A commensurate growth in operational funding has not taken place, resulting in a significant change to the ratio of operating to capital funding, as illustrated in Figure 5. Subatomic physics has been more affected than most disciplines in this respect, given its extraordinary success rate in CFI competitions.

To fully utilize the substantial CFI investments in subatomic physics infrastructure requires additional operating funding in the NSERC envelope. Figure 4 shows that growth in operations funding has not been possible for the past five years, resulting in some activities now being underfunded. Unfortunately, it is not a simple matter to quantify the actual shortfall amount as a fraction of the CFI award amounts.

An analysis of those experimental areas that have received significant CFI funding over the period 2009-2015 (namely those answering questions 1,2,3, and 6) shows that two of these thematic areas (Q1 and Q3) have seen growth in the size of the communities in the past five years without a commensurate increase in operations funding. A supplement of $2M to the envelope would be required to raise the operational funding to match the increased activity in those areas and to return the MRS funding back to the level from five years ago.

(ii) Ramping up next flagship projects

The research plan includes the support of several projects that may develop to be the flagships of the future. Their timelines are not all set well in advance, and the Canadian community will not likely have capacity to embark on all of them, especially if all the existing flagships continue.

“I am originally from the Aundeck Omni Kaning First Nation but completed high school on the Pimichikimak Cree Nation. At UWinnipeg, my multiple summer research experiences, supported by NSERC USRA, were invaluable. My work in experimental subatomic physics at UWinnipeg, where I built and used test setups for electron and proton detectors, on preparations for the Qweak and Nab experiments helped advance my understanding by applying the knowledge I learned in class to a real-world setting.

My summer research experience also helped me gain confidence in myself that has allowed me to complete my BSc in Physics in 2010 from UWinnipeg, along with a Bachelor of Aerospace Engineering and Mechanics (BAEM) from University of Minnesota in 2013. Those summers at UWinnipeg represented a turning point in my career. They really helped me to find something I enjoyed and that I was good at, building and using high-tech equipment.”

MARK ABOTOSSAWAY, BSc, The University of Winnipeg, 2010,
Structural Analysis Engineer, Boeing, Seattle, Washington

In any case, the envelope will need to grow to accommodate ramping up a set of these. Based on the historical trend in ramping up operational support, prior to saturation in 2010, the envelope should grow by $2M over a five year period.

(iii) New opportunity funding

Figure 4 shows how funding of recurring costs (individual, project/group, and MRS grants) has steadily grown to the point where there is little opportunity to support small-scale and short-term R&D efforts (primarily through RTI grants). Previously, when the envelope funded both major and minor equipment costs for projects, the RTI portion was large enough to fund such proposals. RTI funding is especially important for smaller scale capital investments or to support the R&D necessary to advance a larger scale project to the stage where a CFI application would be appropriate.

It is important to restore sufficient “opportunity funds” to be able to start new projects that may develop into major new research initiatives. This requires not only that overall envelope funding be increased by an appropriate amount for this purpose, but also that sufficient information be given to the SAP evaluation section to ensure that “opportunity funds” are available in future years. While there is a general understanding that the funding demands beyond the next year need to be considered, the process for recommending funding levels focuses on balancing the budget for the upcoming fiscal year. The recurring costs for the next five years can be estimated prior to each competition, and with that information the evaluation section can ensure there be “opportunity funds” for future competitions, years in advance. It is clear, however, that in the past five years there has not been any opportunity to protect “opportunity funds” given the extreme pressure on the envelope.

POLICY RECOMMENDATION

Carefully manage the NSERC subatomic physics envelope to allow for new projects to be developed.

Researchers assembling the EMMA mass spectrometer at TRIUMF.

Historically, approximately 5% of the subatomic physics envelope was used for the purpose of developing new experiments and technologies, which helped bring the community to the current suite of projects. Therefore an appropriate increase of the envelope for this purpose would be $1M.

(iv) Increasing support for graduate student training

The survey data, reported in Section 4.1, indicated that the community has the capacity to train more than 200 additional graduate students. Increasing the number of students by 100 over the next five years would require additional funding of about $2M per year, after 5 years. Categories (i)-(iii) will increase opportunities for training at other levels, such as for postdoctoral fellows.

Summary

Table III summarizes the recommended increases to the subatomic physics envelope for the period of this long-range plan. This corresponds to a restrained and efficient program, as expressed in the charge to the Long Range Plan Committee. Significant increases beyond these recommended amounts would allow the community to participate in more of the proposed flagship projects and train more graduate students and post-doctoral fellows.

POLICY RECOMMENDATION

Grow the NSERC subatomic physics envelope by $7M over the next 5 years.

6. Return on Investment

Undergraduate student at work during her First Year Summer Research Experience at TRIUMF.

Subatomic physics research is an impactful field that benefits Canadians in far-reaching ways. The excitement generated by new discoveries in the field can serve to inspire Canadians and can be leveraged as a beacon to attract talented young minds towards dynamic careers in science and technology. Subatomic physics research is also an innovation and technology driver, leading to new commercialization opportunities for private enterprises.

1. CULTURAL BENEFITS: INSPIRING CANADIANS

Canadians celebrated when Arthur McDonald was awarded the Nobel Prize in Physics in 2015 for the discovery of neutrino oscillations. Discoveries in subatomic physics often figure highly in the media because of their appeal to Canadians. Catalyzing curiosity, they spur public interest in science and provide opportunities to enrich science culture in Canada. These directly support the first strategic goal of NSERC 2020: "Fostering a Science Culture in Canada."

SUBATOMIC PHYSICS RESEARCH SUPPORTS THE GOALS OF NSERC 2020:

Goal 1

Fostering a science and engineering culture in Canada
Physics students often cite subatomic and astrophysics discoveries as their chief reasons for wanting to study physics. High profile discoveries in these fields can spur public interest in science and foster a vibrant science culture in Canada.

Goal 2

Launching the new generation
The highly collaborative nature of subatomic physics research in Canada is a great benefit to young researchers entering the system, providing them with structure and mentoring by more senior researchers.

Goal 3

Building a diversified and competitive research base
Subatomic physics research is world-class and multidisciplinary, and driven by discovery. The field possesses many training opportunities for building this research base.

Goal 4

Strengthening the dynamic between discovery and innovation
Subatomic physics is a technology driver with strong potential for commercializable technology development. This can lead to the creation of new companies which drive the economy and ultimately leads to job creation. Highly qualified personnel trained in subatomic physics are well suited for a broad variety of jobs in the high-tech sector.

Goal 5

Going global
Subatomic physics is already a global enterprise, with Canadians participating in international collaborations in Japan, at the South Pole, at the Large Hadron Collider in Geneva, and elsewhere. The availability of unique facilities like TRIUMF, SNOLAB, and Perimeter Institute in turn attracts the world's top researchers to Canada.

Subatomic physics encourages students towards careers in science. A recent Institute of Physics report entitled "Particle physics — it matters" describes a survey of physics students at universities in the UK. Students consistently cited subatomic physics and astrophysics as the most popular subject areas in terms of attracting them to study physics.

One way to gauge the public's thirst for knowledge in subatomic physics is to look at the impressive success of science outreach events and programming hosted by the Perimeter Institute, TRIUMF, SNOLAB, and universities across Canada that aim to promote science and ignite Canadians' sense of curiosity. TRIUMF, UBC, and SFU jointly present a Saturday morning lecture series on Frontiers of Modern Physics. TRIUMF's public tour reached 1,900 members of the general public in 2015. SNOLAB's underground tour welcomed 500 attendees in 2015.

There is also direct encouragement of high-school students towards careers in science and research. TRIUMF, the University of Victoria, Simon Fraser University, and McGill University hold annual particle physics masterclasses, where high-school students become particle physicists for the day and analyze real data from the ATLAS experiment. SNOLAB has a similar masterclass program. TRIUMF also sponsors a high-school fellowship, which includes a six-week summer research experience at TRIUMF. The labs also support high-school teacher training. For example, in 2015, SNOLAB supported the winner of the CAP high-school teacher award to spend a week working with researchers on the various ongoing experiments. Perimeter Institute's outreach programs reach an impressive number of primary and secondary school students, by providing their teachers with well-developed classroom activities in physics. The use of new media to encourage public interest in science by Perimeter Institute, TRIUMF, and SNOLAB is also impressive.

2. EDUCATIONAL BENEFITS: TRAINING HIGHLY QUALIFIED PERSONNEL

To answer the big questions in physics requires highly qualified personnel (HQP). These HQP generate ideas on innovative avenues of investigation to design, build, and operate the experiments and facilities as well as to devise algorithms to search for the elusive physics signals in the collected data, to statistically analyse the results, and to create the numerical simulations to confront theoretical expectations with reality. Training of HQP in subatomic physics is realized by involving undergraduate and graduate students in research programs and employing early-career PhDs and technical staff at all stages of their careers. There are additional training opportunities for graduate students at summer schools like TSI at TRIUMF and TRISEP, a Canadian tri-institute summer school on elementary particle physics organized yearly by Perimeter, SNOLAB, and TRIUMF.

Table IV shows an overview of the average number of MSc and PhD graduate students currently being trained in subatomic physics in Canada per full-time equivalent faculty, broken down by the research area of their supervisors. These numbers are from the community survey described in Chapter 4. The 171 respondents of the survey are currently training an average of approximately 2.1 graduate students per faculty, with the PhD to MSc ratio being 3 to 2. The survey data indicated that the community has the capacity to train about 80% more students, if additional funding were available.

A study was conducted within ATLAS-Canada on the career paths of their students and postdocs after the completion of their degrees or contracts, to see how these HQP contributed to society. Since the start of ATLAS-Canada in 1992, the sum of all MSc, PhD and postdoctoral fellows in training or trained exceeds 300 HQP, approximately evenly

Area of research	MSc/FTE	PhD/FTE	Total/FTE
Theory	0.9	1.3	2.2
Experiment	0.8	1.3	2.1
Overall	**0.9**	**1.3**	**2.1**

TABLE IV
Overview of the average number of MSc and PhD graduate students currently being trained in subatomic physics in Canada per full-time equivalent (FTE) faculty, broken down by the research area of their supervisors.

divided between the three categories. Much of this graduate student training has occurred since the start of the LHC in 2009. Out of the completed degrees or postdoctoral appointments for which information was available in the previous approximately 5 years to fall 2014, the following fractional breakdowns of subsequent HQP activity were identified:

- 70% of MSc students continued on to do a PhD (mainly remaining in the same field), while the remaining 30% found employment in research, industry, or education.
- 40% of PhD students remained in research, 30% went to industry, another 20% became teachers, while the remaining 10% were employed in other areas of society.
- 70% of postdocs trained remained in research, 20% went to employment in industry, while the remaining 10% were employed in other areas of society.

In summary, nearly all of the personnel trained in ATLAS-Canada either remained in research or moved on to contribute to education or industry. Data of this sort from the broad community of subatomic physics would be helpful to track employment for the entire discipline.

3. TECHNOLOGICAL BENEFITS: APPLICATIONS OF SUBATOMIC PHYSICS

Subatomic physics research benefits a variety of related fields. Examples are imaging technologies in nuclear medicine, cancer treatments, sterilization of blood and other medical items, oil-well logging, ion implantation of semiconductors, the most common type of smoke detectors, forensic analysis, monitoring cargo for contraband, and of course commercial power generation.

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

An active research program in subatomic physics leads to a nimbleness to respond to crises, such as the medical isotope crisis of recent years. In late 2007, the world experienced a critical shortage of the medical-isotope molybdenum-99 (MO-99) over a period of several weeks due to an extended shutdown of AECL’s NRU reactor in Chalk River, Ontario. The shortage forced the cancellation and delay of diagnostic testing for life-threatening conditions affecting tens of thousands of patients throughout the U.S. and Canada. Researchers in Canada from subatomic physics, accelerator physics, and medical physics proposed alternative solutions for medical isotope production (“Making Medical Isotopes, Report of the Task Force on Alternatives for Medical-Isotope Production,” TRIUMF AAPS). Successful research programs were supported by NRCan and CIHR. Two groups containing subatomic and accelerator physics researchers were supported by the NRCan Isotope Technology Acceleration Program (ITAP), in 2013: the CycloMed99 consortium and the Prairie Isotope Production Enterprise (PIPE). In February 2015, the CycloMed99 team was awarded the NSERC Brockhouse Canada Prize for Interdisciplinary Research in Science and Engineering. This incredibly successful and rapid progress could not have been made without subatomic physics researchers.

There are several new therapy and imaging possibilities opened up by the availability of new isotopes. Research at TRIUMF is now expanding into new alpha-emitting isotopes such as ^{211}At and ^{225}Ac, which may be used for cancer therapy, produced at ISAC and ARIEL. The functionality of these isotopes may be studied with ^{209}At, which is a gamma-emitter that can be used for functional imaging.

According to CERN’s “Accelerating science and innovation — Societal benefits of European research in particle physics,” the nuclear medicine imaging market is an estimated $15 billion per year, and is growing 10% annually. Accelerator-produced medical isotopes and imaging technologies are important areas where the Canadian subatomic physics community is poised to have a sustained impact.

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. CERN's "Accelerating science and innovation — Societal benefits of European research in particle physics" details the impact that this research has had on international industry. The World Wide Web stimulates $2.3 trillion in annual commercial traffic, a huge return on the $1.5 billion spent annually at CERN and the world's other 200 research particle accelerators. The World Wide Web is now considered key to the sustainable development globally; for example, the UN's sustainable development goals 2016-2030 include internet users (per 100 people) as a world development indicator for infrastructure. In 2010, cloud and grid computing was valued as a $50-million industry. Today they have grown into huge industries, with many companies relying on these resources to conduct their business on a daily basis. Tier-1 grid computing is a particular expertise in Canadian high-performance computing. New advances in cloud computing for particle physics are also being made.

Worldwide accelerator production is a $2-billion industry, with 1,000 accelerators sold yearly for applications ranging from semiconductor processing, producing short-lived isotopes for medical imaging, accelerator mass spectrometry, to radiation therapy. The collective value of the products made using accelerator technology, including isotopes used in determining the age and origin of materials, studying the behavior of defects and impurities of materials, and medical applications has been estimated at more than $500 billion per annum. Canada is one of six countries worldwide with industrial capacity to produce the superconducting radiofrequency (SRF) cavities needed in particle accelerators, which have applications not only for research at facilities like TRIUMF, but also in the energy, defence, aviation, aerospace and research industries to provide very precise metal-welding services using electron beams and in environmental protection by replacing chemicals with electrons to treat flue gas that is emitted by coal-burning power plants. Canada developed its SRF production capabilities through pioneering work first done at TRIUMF, who then worked with PAVAC Industries, Inc., effectively transferring the technology to industry.

Another example is Canada's long history of achievements in nuclear energy. CANDU reactors were developed in the 1950s and 60s and the design is still used today. Canadian nuclear researchers have taken a leading role in a recently initiated International Atomic Energy Agency Coordinated Research Project for the "Development of a Reference Database for Beta-Delayed Neutron Emission." This directly enhances knowledge and calculational capabilities in the fields of nuclear energy, safeguards, used fuel and waste management, and nuclear sciences. SRF technology might also be used for Generation IV accelerator-driven reactors, a project in which PAVAC is already involved.

These are just a few of the ways that fundamental subatomic physics research in Canada continues to have a substantial impact on society at large.

4. DIRECT ECONOMIC IMPACTS: INDUSTRIAL CONNECTIONS

Subatomic physics research develops innovations, creating new companies and spurring opportunities for Canadian industry. This in turn results in job creation and economic development in the high-tech sector. The following examples represent companies and new products that have a direct relationship to subatomic physics research and technology development in Canada.

MODCC: The global mineral industry collects data constantly for the purpose of decision-making on issues such as where to look for minerals, what metals and minerals to mine, where to mine, how quickly to mine, how mines should be designed and built. Data are produced through activities such as exploration, surveying, drilling, blasting, assaying, transporting the rockmass to the mill, characterizing the mine's geology, and through mine planning, among many others. Data analysis tools and expertise from SNOLAB can be used to process these data. In 2013, the Mining Observatory Data Control Centre (MODCC) was created in SNOLAB's above-ground facilities. MODCC is a four-year, $2,425,000 project that resulted from a partnership between the Centre for Excellence in Mining Innovation (CEMI), SNOLAB, the Canada Mining Innovation Council (CMIC), and the Northern Ontario Heritage Fund Corporation (NOHFC). Data analysts will use analysis techniques developed at SNOLAB to develop data tools for the mining and exploration industries.

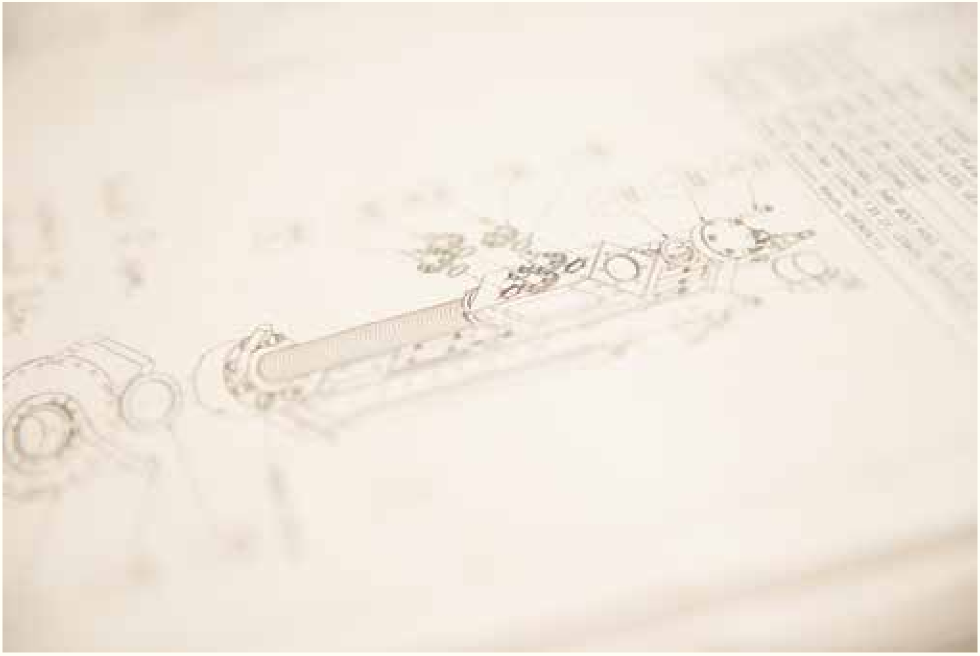
Bubble Technology Industries Inc.: BTI is a technology firm with expertise in the field of radiation and explosives detection. The company provides commercial products, radiation services, consulting, and contract research and development to a wide range of clients including law enforcement and first-responder organizations, defense and space agencies, regulatory and international standards groups, research institutions, and national security agencies. The skills acquired by HQP in experimental subatomic physics research are often desirable to companies like BTI. There are a number of prominent recent graduates in the field who have gone on to successful careers in private industry working for BTI.

AAPS: TRIUMF's Advanced Applied Physics Solutions Inc. (AAPS) was formed through the Networks of Centres of Excellence program as a Centre of Excellence for Commercialization and Research (CECR) in spring 2008. Since then, AAPS has graduated from the CECR program and launched five companies: ARTMS Products, CRM Geotomography Technologies, Frontier Sonde Inc., IKOMED, and Micromatter Technologies.

ARTMS Products Inc.: ARTMS was created as a commercial venture resulting from the successful research conducted by the CycloMed99 collaboration, a TRIUMF-led national consortium supported by Natural Resources Canada's Isotope Technology Acceleration Program (ITAP). The company is targeting areas where access to Mo-99/Tc-99m has been restricted in the past (e.g. Asia) and in countries where the cost of Mo-99/Tc-99m is currently high (e.g. the UK). In the longer-term, cyclotron-produced Tc-99m could become a widely accepted method of production for this critically important isotope. In addition to commercializing the production process, ARTMS is developing a commercial scale process for recycling the enriched Molybdenum-100 target material.

Cosmic Ray Muon Geotomography Technologies Inc.: CRM Geotomography develops advanced muon geotomography technology, for near-mine exploration for life extension of underground base- and multi-metal mines. The company is built on technology developed by subatomic physicists to detect muons. In this application, muon telescopes are placed underground in a mineshaft. Large, high-density ore deposits located near the mineshaft scatter muons, which can be detected by the telescopes. This indicates the best direction in which to search for new deposits. The technique is similar to a CAT scan for humans, with the X-rays replaced by cosmic muons. They are also investigating other applications of the technology, such as container scanning for border and port security and management of nuclear materials and waste.

Frontier Sonde Inc.: The use of well-logging tools ("sondes") is an essential feature of the oil and gas industries. FSI has developed a new fast-neutron probe, which incorporates both gamma-ray and neutron detectors and can be present in the borehole during drilling operations. Fast neutrons



can readily penetrate metal or cement casings and provide the required information on oil-abundant zones and water flow. The greatest demand presently for this new technology is in China, but it will also find application in all major mining jurisdictions which are currently using Enhanced Oil Recovery (EOR) technologies. The probe could also find application in shale oil or gas, or coal-bed methane exploration. Field trials are set to commence in 2016.

IKOMED: Fluoroscopy is a medical imaging technology that is widely used to create real-time movies of internal body structures using X-rays. Fluoroscopy is used to guide minimally invasive surgical interventions where catheters or tools are inserted percutaneously in order to diagnose and treat internal organs. IKOMED has developed a technology that can potentially reduce the radiation exposure of a fluoroscopy procedure up to five-fold without image degradation. IKOMED's solution allows for different radiation doses to be delivered to different parts of the image, with the highest delivered in the region of interest. It is anticipated that a fully integrated IKOMED system will be tested on humans in 2016 and released to market.

Micromatter Technologies Inc.: This company manufactures stripper foils for accelerators, thin-film standards for X-ray fluorescence analysis applications, and thin windows for radiation detectors. The company is a spin-off of mature technology used at TRIUMF to create stripper foils used in the proton beam extraction from the TRIUMF cyclotron. The coating technology has a wide range of applications. The company recently moved into its own office space in Surrey, BC's burgeoning Innovation Boulevard.

ACSI: Advanced Cyclotron Systems Inc. (ACSI) is a world leader in the design and manufacturing of medical cyclotrons, including those used in the production of radioisotopes for PET and

SPECT imaging. ACSI has been building cyclotrons for over 20 years. The company's lineage can be traced back to EBCO Industries, an affiliated company that helped build TRIUMF's original 500 MeV cyclotron over 40 years ago. ACSI is now the third largest supplier of medical cyclotrons in the world and currently employs approximately 50 full-time staff.

D-Pace: Founded in 1995, Dehnel-Particle Accelerator Components and Engineering Inc. (D-Pace) provides state-of-the-art engineering products and services to the particle accelerator industry. D-Pace's founder and president, Dr. Morgan Dehnel, received his graduate training at TRIUMF. D-Pace specializes in complete beam line system designs, charged particle transport systems, as well as components for cyclotrons, ion implanters, and linear accelerators. D-Pace also offers its expertise to clients around the world, ranging from semiconductor producers to advanced research facilities. D-Pace has grown into a successful business with a strong reputation as well as an international reach to customers in France, Japan, South Korea, Taiwan, the Netherlands, and the United States. D-Pace employs 10.5 full time employees, including research scientists and engineers. In 2007, the successful collaboration between TRIUMF and D-Pace was recognized by the Government of Canada with an NSERC Synergy Award.

Nordion: Founded in 1946, Nordion is a global health sciences company offering over 30 products to over 500 clients in 40+ countries around the world. TRIUMF has worked closely with Nordion for over 35 years, with their Vancouver operations located on the TRIUMF campus. This unique collaboration has produced several pioneering developments including the production of high-purity iodine-123, used for the management of thyroid cancer as well as imaging cardiac and neurological disorders, and a patented high-volume production method for palladium-103, used in leading edge brachytherapy treatments for prostate, breast, and other cancers. Other isotopes produced at TRIUMF include gallium-67, thallium-201, and indium-111. Recently, TRIUMF and Nordion have collaborated on research related to the production and sale of strontium-82. In 2004, the TRIUMF-Nordion relationship was recognized by the Government of Canada with an NSERC Synergy Award. Given TRIUMF's significant contributions to this relationship, it is clear that Nordion's Vancouver operations could not exist without the support of the national laboratory's infrastructure and expertise. The site produces over 2.5 million patient isotope doses per year: 15% of Canada's total. The partnership supports the employment of some 40 Nordion staff, as well as 30 TRIUMF employees who operate the isotope production facility, the cost of which is fully covered by Nordion.

PAVAC Industries Inc.: PAVAC develops hybrid electron beam technology for industrial applications. In April 2008, as a result of a partnership with TRIUMF, PAVAC became one of a very select group of manufacturers capable of producing superconducting radio-frequency (SRF) cavities. These superconducting devices are assembled into modules to form next-generation accelerators with applications ranging from health care and environmental mitigation and remediation to advanced materials science and high-energy physics. The TRIUMF-PAVAC collaboration in SRF cavity production has unlocked new advanced manufacturing capabilities for Canada and has established the nation as one of only six in the world with the industrial capability to produce this technology. This has enabled PAVAC to bid for other projects at major laboratories and institutions around the world and has triggered the rapid growth of the firm. PAVAC has grown from a 3,000-sq. ft. facility with six employees to a new 100,000-sq. ft. facility with 58 employees.

> “My residency was at Mayo Clinic, and I believe my particle physics background was a significant reason I was chosen. During my three-year residency, Mayo Clinic was building and commissioning a proton therapy centre. The particle accelerator they use is a synchrotron system from Hitachi, and of course I was already familiar with much of the physics involved. Along with my clinical rotations at Mayo, I completed a number of research projects all geared towards preparations for the first proton treatments. These included Monte Carlo simulations used for hardware design, radiobiological studies, and a clinical study which improved the immobilization and set-up reproducibility of head-and-neck cancer patients.”
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> **LORRAINE COURNEYEA**, PhD, University of Victoria 2011 on ATLAS; Medical physicist at Sunnybrook Health Sciences Centre (Odette Cancer Centre), Toronto

CRIPT: In 2013, subatomic physics researchers from Carleton University unveiled a large scanning device which uses cosmic ray muons. The prototype scanner built at Carleton is capable of imaging containers and providing a signal indicating the presence of high density nuclear materials such as uranium or plutonium. The Cosmic Ray Inspection and Passive Tomography (CRIPT) system obtains three-dimensional images of a container’s content using muons, naturally occurring, high-energy rays that can pass through metres of steel. When muons pass through very dense materials like uranium, plutonium or lead, they are deflected by small amounts. CRIPT detectors measure these deflections very precisely. CRIPT passed its final milestone in 2013 when an air cargo container was scanned. CRIPT was developed in collaboration with Defence Research and Development Canada, Atomic Energy Canada Ltd, the Canada Border Services Agency, Health Canada, AAPS, and International Safety Research of Ottawa. The project was funded through the former Chemical, Biological, Radiological-Nuclear and Explosives Research and Technology Initiative (CRTI), a federally funded program led by Defence Research and Development Canada’s Centre for Security Science.

NOBEL PRIZE IN PHYSICS 2015

Professor Emeritus Arthur McDonald from Queen's University is the co-winner of the 2015 Nobel Prize in Physics, along with Takaaki Kajita of the University of Tokyo, "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

A neutrino puzzle that physicists had wrestled with for decades had been resolved. Compared to theoretical calculations of the number of neutrinos produced by energy production reactions in the Sun, up to two thirds had been missing in previous measurements performed on Earth. The research group led by Arthur McDonald at the Sudbury Neutrino Observatory (SNO) could demonstrate that neutrinos from the Sun were not disappearing on their way to Earth and were captured with a different identity when arriving at SNO. The discovery led to the far-reaching conclusion that neutrinos, which for a long time were considered massless, must have some mass, however small. For particle physics this was a historic discovery. Its Standard Model of the innermost workings of matter had been incredibly successful, having resisted all experimental challenges for more than twenty years. However, as it requires neutrinos to be massless, the new observations had clearly shown that the Standard Model cannot be the complete theory of the fundamental constituents of the universe.

The SNO experiment, located two kilometres underground in the active Vale Creighton nickel mine near Sudbury, Ontario, has pushed boundaries in low background techniques to measure neutrinos at a rate of about one per hour in a kilotonne of heavy water as a detection medium, with unprecedented accuracy.

The worldwide recognition for the fundamental research undertaken by Arthur McDonald and the team at SNOLAB is a tremendous source of pride and satisfaction. It reflects very well on the commitment placed by Canadian funding agencies and institutions on helping Arthur McDonald achieve the project's goals; on the expert capabilities of the science team; and on how successful SNO was to attract talent inside and to Canada and nurture it.

The Nobel Prize is the highest award in science. It recognizes the Canadian investment in Canadian Subatomic Physics, which has allowed this group of Canadian and international scientists to make a remarkable impact on science.

"While I am a co-winner of the Nobel Prize, the honour really represents a culmination of the hard work and contributions of Canadian and international colleagues with whom I have collaborated during my career," said Arthur McDonald. The success of the groundbreaking research at the Sudbury Neutrino Observatory is due in large part to his persistence, dedication and leadership. In addition to these qualities, Arthur McDonald's insight, ingenuity and drive have been and continue to be an inspiration for all who had the privilege to benefit from his guidance.

Arthur McDonald was recognized in the House of Commons in Ottawa on March 8, 2016, along with his collaborators representing four countries and more than 15 universities and research facilities.

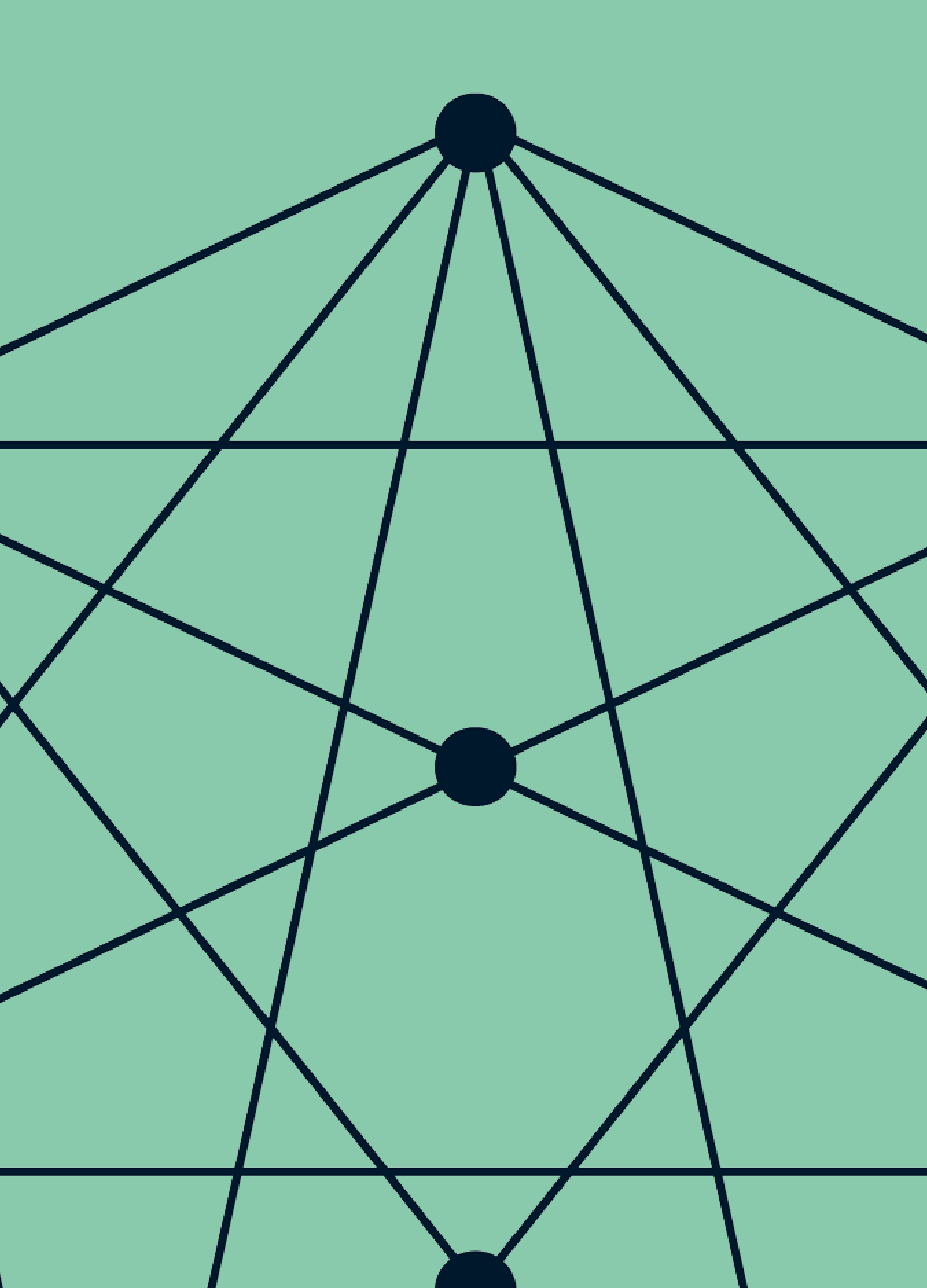
For his research, Arthur McDonald has received a number of awards and recognitions, including the

Canadian representatives at the Nobel Prize Ceremony in Stockholm, Sweden, on December 10, 2015. The prize was presented to SNO director Arthur McDonald (bottom left). He was accompanied by George Ewan (Queen's, front middle), David Sinclair (Carleton and TRIUMF, front right), Doug Hallman (Laurentian, top left), Davis Earle (Queen's, top middle), and Aksel Hallin (Alberta, top right).

Gerhard Herzberg Canada Gold Medal for Science and Engineering in 2003, the highest honour of the Natural Sciences and Engineering Research Council of Canada. Also in 2003, he received the CAP's Medal for Lifetime Achievement in Physics, and was named a Companion of the Order of Canada in 2015.

A very active Professor Emeritus since 2013, Arthur McDonald earned his PhD in 1969 from the California Institute of Technology. He worked at Chalk River Nuclear Laboratory from 1970 to 1982 and was on the faculty at Princeton University from 1982 to 1989. He joined Queen's Department of Physics, Engineering Physics and Astronomy in 1989 and served as the director of SNO. He was the inaugural holder of the Gordon and Patricia Gray Chair in Particle Astrophysics at Queen's.

The success of SNO, which has granted close to 90 MSc and PhD theses (of which 63 are Canadian), has led to the expansion of the experiment into a cutting-edge research facility now known as SNOLAB. The facility was constructed with funds from federal, provincial and regional agencies. It is operated by the SNOLAB Institute whose member institutions are Queen's University, Carleton University, Laurentian University, University of Alberta and Université de Montréal.



A. Glossary

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

ANL (Argonne National Laboratory): A DOE national laboratory in Argonne, Illinois, which is home to a number of facilities, including the ATLAS heavy-ion accelerator.

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

ATLAS (A Toroidal LHC Apparatus): An experiment at the CERN Large Hadron Collider, primarily detecting the collision products of proton-proton collisions.

BaBar: A *B*-hadron physics experiment that studied the particles produced in collisions between electrons and positrons accelerated by the PEP-II collider at the SLAC National Accelerator Laboratory.

Belle II: A *B*-hadron physics experiment at the SuperKEKB electron-positron collider in Japan that will begin to take data within this five-year plan.

BNL (Brookhaven National Laboratory): A multipurpose research institution located on Long Island, New York.

BRIKEN (Beta-delayed neutron studies at RIKEN): A large ^{3}He-long counter neutron detection array with an implantation detector which will take data at RIBF from 2016 onwards.

BSM (Beyond the Standard Model): As yet undiscovered physics necessary to formulate a complete description of matter and forces.

CANARIE: CANARIE operates and evolves the national backbone of Canada's ultra-high-speed National Research and Education Network (NREN), providing the national and international networking for Canada's subatomic physics community.

CANREB (CANadian Rare-isotope facility with Electron-Beam ion source): A CFI-funded initiative that will improve the purity of rare ion beams delivered by ARIEL to ISAC.

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

CERN (the European Organization for Nuclear Research): International laboratory for nuclear and particle physics located on the French-Swiss border near Geneva.

CFI (Canada Foundation for Innovation): Created by the Government of Canada in 1997, CFI makes investments in state-of-the-art research facilities and equipment in a wide variety of scientific disciplines.

CINP (Canadian Institute of Nuclear Physics): A formal organization of the Canadian nuclear physics research community to promote excellence in nuclear research and education, and to advocate the interests and goals of the community both domestically and abroad. It gathered input from the Canadian nuclear physics research community for this document.

CLIC (Compact Linear Collider): A study based in Europe for a high-energy and high-luminosity collider aiming at accelerating and colliding electrons and positrons at a nominal energy of 3 TeV.

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.

CREX (Calcium Radius Experiment): Experiment at JLab to measure the neutron radius of ^{48}Ca.

DEAP (Dark matter Experiment using Argon Pulse shape discrimination): DEAP-3600 is a dark matter experiment searching for direct detection of weakly interacting massive particles using scintillation in 3.6 tonnes of liquefied argon at SNOLAB. Data talking is planned to start in 2016. A 50-tonne upgrade is under consideration.

DeepCore: The DeepCore low-energy extension is a densely instrumented region of the IceCube array, which extends the observable energies to below 100 GeV.

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

DOE (Department of Energy): The United States Department of Energy, which operates a number of national laboratories across the USA.

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

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

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

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

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

EURICA (EUroball-RIKEN Cluster): γ-ray nuclei spectroscopy project at RIKEN.

EXO (Enriched Xenon Observatory): An experiment seeking to measure neutrinoless double beta-decay in ^{136}Xe. The EXO-200 experiment is currently located at the WIPP facility in New Mexico, USA. A substantially larger next-generation detector nEXO is proposed for SNOLAB.

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

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

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

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

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

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

HALO (The Helium and Lead Observatory): A long-term, low-cost, high-livetime, and low-maintenance dedicated supernova detector running at SNOLAB.

HIGS (High Intensity Gamma-Ray Source): A free-electron-laser-based Compton backscattering gamma-ray source at Duke University.

HL-LHC (High-Luminosity LHC): The high-luminosity running phase of the LHC expected to begin in 2026.

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

IceCube: A particle detector at the South Pole encompassing a cubic kilometer of ice.

ILC (International Linear Collider): A proposed linear particle accelerator with planned collision energy of 500 GeV initially, with the possibility for a later upgrade to 1 TeV.

ILD (International Large Detector): A detector proposed for the ILC.

IPP (Institute of Particle Physics): A formal organization that promotes Canadian excellence in particle physics research and advanced education. It gathered input from the Canadian particle physics research community for this document.

IRIS (ISAC Charged Particle Spectroscopy Station): A rare-isotope reaction spectroscopy station utilizing reactions with a frozen (solid) hydrogen target.

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

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

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

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

J-PARC (Japan Proton Accelerator Research Complex): Joint project between KEK and the Japan Atomic Energy Agency, which hosts the proton accelerator used in the T2K experiment.

KEK (High Energy Accelerator Research Organization and National Laboratory): Laboratory located in Japan specialising in neutrino and *B*-hadron physics.

KEKB (KEK B-physics): An Asymmetric Electron-Positron Collider for *B*-hadron Physics located at KEK. It hosts the Belle II experiment.

LBNF/DUNE (Long-Baseline Neutrino Facility/Deep Underground Neutrino Experiment): Dual-site experiment for neutrino science and proton decay studies, hosted by Fermilab and the Sanford Underground Research Facility.

LEP (Large Electron-Positron Collider): Electron-positron collider that used to be sited at CERN.

LHC (Large Hadron Collider): A proton and heavy ion collider at CERN which hosts the ATLAS, CMS, LHCb, and ALICE experiments.

MAMI (Mainz Microtron): An electron accelerator facility, located on the campus of the Johannes Gutenberg University of Mainz, Germany.

MOLLER (Measurement of a lepton-lepton electroweak reaction): An experiment to measure the parity-violating asymmetry in electron-electron (Moller) scattering at Jefferson Lab.

MRS (Major Resources Support): NSERC program to facilitate the effective access by Canadian academic researchers, working in the field of subatomic physics, to major and unique national or international (based in Canada) experimental or thematic research resources by financially assisting these resources to remain in a state of readiness for researchers' to use.

NA62: Experiment at the CERN Super Proton Synchrotron to measure the rare kaon decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$.

NEWS (New Experiments With Spheres): Collaboration developing gaseous spherical proportional counters for multiple particle detection purposes. NEWS-SNO is a project related to direct dark matter detection, proposed for SNOLAB.

nEXO (The next phase of the Enriched Xenon Observatory): A next-generation experiment searching for neutrinoless double-beta decay in 5 tonnes of liquefied xenon enriched in ^{136}Xe, proposed for SNOLAB.

NSERC (Natural Sciences and Engineering Research Council of Canada): An agency of the Government of Canada that supports university students in their advanced studies, promotes and supports discovery research, and fosters innovation by encouraging Canadian companies to participate and invest in postsecondary research projects.

NuPRISM: Proposed intermediate water Cherenkov detector for the J-PARC neutrino beam.

PI (Perimeter Institute for Theoretical Physics): Centre for scientific research, training and educational outreach in foundational theoretical physics based in Waterloo, Ontario.

PICO (formed from the merger of two existing groups, PICASSO and COUPP): Experiment searching for direct detection of dark matter with bubble chambers operated with 40 kg of superheated liquids and located at SNOLAB. A 500 kg version is in development.

PINGU (Precision IceCube Next Generation Upgrade): The low energy extension of IceCube to detect the atmospheric neutrino oscillation below 10 GeV.

PREX (^{208}Pb Radius Experiment): PREX uses the parity violating weak neutral interaction to probe the neutron distribution in ^{208}Pb at JLab.

Qweak: A precision test of the Standard Model and determination of the weak charges of the quarks through parity-violating electron scattering at JLab.

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

RHIC (Relativistic Heavy Ion Collider): Heavy-ion collider at Brookhaven National Laboratory in the USA.

RIB: Rare Isotope Beam.

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

RIKEN (The Institute of Physical and Chemical Research): Japan's largest comprehensive research institution that performs research in a diverse range of scientific disciplines, including physics, chemistry, medical science, biology and engineering.

RTI (Research Tools and Instruments): NSERC program to financially support research tools and instruments.

SAP (SubAtomic Physics): The broader field of nuclear and particle physics, comprising all knowledge taking place at scales smaller than that of the atom.

SHARC (Silicon Highly-segmented Array for Reactions and Coulex): A multi-purpose array for charged-particle detection which offers unique capabilities when integrated with the TIGRESS gamma-ray detectors and the post-accelerated beams at the new ISAC-II facility.

SLAC (Standford Linear Accelerator): SLAC National Accelerator Laboratory is a U.S. Department of Energy Office of Science laboratory operated by Stanford University.

SM (Standard Model): The Standard Model of elementary particle interactions.

SNO (Sudbury Neutrino Observatory): Original solar neutrino physics experiment located deep underground in Sudbury. Solved the solar neutrino problem.

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 and geo-neutrinos using a liquid scintillator instead of heavy water.

SNOLAB (Sudbury Neutrino Observatory Laboratory): A deep underground facility in Sudbury, Ontario, specializing in neutrino physics and the search for dark matter.

SoLID (Solenoidal Large Intensity Device): A high luminosity, large acceptance detector proposed for Jefferson Lab Hall A that makes use of the former CLEO solenoid magnet.

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

SuperCDMS (Cryogenic Dark Matter Search): A dark matter experiment searching for direct detection of weakly interacting massive particles using cryogenic germanium detectors. After a brief testing period located at the Soudan mine MN, SCDMS is planning to relocate to SNOLAB.

SuperFRS (Super Fragment Separator): The SuperFRS is a proposed large-acceptance superconducting fragment separator followed by different experimental branches including a combination with a new storage-cooler ring system at GSI.

T2K (Tokai to Kamioka): A long baseline experiment from J-PARC to the Super-Kamiokande neutrino detector in Japan to study the physics of neutrino oscillation.

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 and accelerator-based science.

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

TUEC (TRIUMF User-group Executive Committee): An elected body of seven members designed to manage the business and affairs of the TRIUMF Users Group.

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

VERITAS (Very Energetic Radiation Imaging Telescope Array System): A major ground-based gamma-ray observatory with an array of four 12-meter optical reflectors for gamma-ray astronomy in the GeV to TeV energy range, located at Mount Hopkins, AZ, USA.

B. 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 (LRP). 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 2011-2016, in addition to providing an assumption-based forecast for the period 2016-2021. Since then, the time lines of some experiments and future projects have evolved, and new research opportunities may have emerged. A new LRP exercise is to be conducted. It will cover the period 2017-2021 and include a look ahead to 2026.

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 Long-Range Plan. 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:

- Chair of the Subatomic Physics Evaluation Section
- Director of the Canadian Institute of Nuclear Physics
- Director of the Institute of Particle Physics
- TRIUMF's Director or Head of the Science Division

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 (i) the ever increasing internationalization of projects and collaborations in addressing the fundamental questions of subatomic physics, (ii) the concurrent requirement to maintain and further develop world-class domestic research programs and infrastructure, (iii) the established expertise and strengths of the Canadian community and (iv) the recognition of the fact that the Canadian subatomic physics community cannot be involved in all research endeavours, the Committee is asked to identify subatomic physics scientific ventures and priorities that should be pursued by the community on a five- to ten-year horizon and that would ensure continuous Canadian global scientific leadership. Budgetary estimates must be provided as well, including funding ranges for prioritized endeavours. These ranges should include funding levels that would allow for a restrained, yet efficient, contribution to the ventures, as well as 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. The Committee may also be asked by NSERC to comment on possible changes to the structure of the programs within the NSERC Subatomic Physics envelope, such as changes in application requirements or in the types of grants available.

IV. PROCESS AND TIME LINE

The LRP Committee membership will be completed by the end of May 2015, and a kickoff meeting will be held immediately after.

The Canadian Institute of Nuclear Physics and the Institute of Particle Physics 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 October 1, 2015; they will be forwarded to the LRP Committee. The Institutes 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) in late 2015 and early 2016, after receiving the briefs. Face-to-face or phone meetings of the Committee will then be held up to the spring of 2016. A final report is to be provided to NSERC no later than September 1, 2016.

V. DELIVERABLES

The LRP Committee will submit its final report to NSERC no later than September 1, 2016. The report will be publicly released, thereafter, in both official languages.

VI. CONFLICTS OF INTEREST AND CONFIDENTIALITY

All members must strictly comply with the Code of Ethics and Business Conduct for Members of NSERC Standing and Advisory Committees. 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.

C. Long Range Plan Committee Membership

Name	Institution
Dean Karlen (Chair)	University of Victoria and TRIUMF
Philip Burrows	Oxford University, United Kingdom
Jens Dilling	TRIUMF
Jacques Farine	Laurentian University
Mark Huyse	K.U. Leuven, Belgium
Randy Lewis	York University
Jeffery Martin	University of Winnipeg
Erich Poppitz	University of Toronto
Achim Schwenk	T.U. Darmstadt, Germany
Manuella Vincter	Carleton University
Andreas Warburton	McGill University
Garth Huber (ex-officio)	CINP Executive Director
J. Michael Roney (ex-officio)	IPP Director
Reiner Kruecken (ex-officio)	Deputy Director, TRIUMF
Nigel Smith (ex-officio)	Director, SNOLAB
Adam Ritz (ex-officio)	SAPES, co-Chair 2016
Olivier Gagnon (observer)	Senior Programs Officer, CFI
Sarah Overington (observer)	Team Leader, NSERC

PHOTO CREDITS

Paul Joseph and TRIUMF
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Dean Karlen
Page 38

Roy Langstaff
Page 41

Queen's University and Michael Fergusson
Page 85

Natural Sciences
and Engineering Research Council
of Canada
350 Albert Street
Ottawa, ON
K1A 1H5
www.nserc-crsng.gc.ca

For further information:
Dean Karlen
University of Victoria and TRIUMF
Chair of the 2017-2021 Long-Range
Planning Committee
(250) 721-6585
karlen@uvic.ca