The Status and Future of Canadian Subatomic Physics

NSERC/CAP Review of Physics
Subatomic Physics Subcommittee

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Executive Summary

Subatomic physics is the field that deals with the properties and interactions of the elementary particles that make up the universe. This field has flourished throughout the twentieth century and has radically altered our understanding of fundamental particles and forces. It has developed a very successful theory, referred to as the Standard Model, which explains matter in terms of three families of particles and four forces. This theory is being tested to the limits of our technical abilities, and has repeatedly proven itself to be accurate.

Despite the success of the Standard Model, there remain many fundamental questions. To illustrate, we have listed a few of the problems that are under active investigation. Gravity does not have a good quantum theory. The Standard Model does not predict time reversal non-invariance, neutrino oscillations, or the masses of the various fundamental particles. The Big Bang model integrates the field of subatomic physics with cosmology but presents us with several interesting problems. We are challenged to explain why there is more matter than antimatter in the universe, the abundances of the various elements due to the nuclear reactions that occurred during the Big Bang, stellar evolution, and supernovae, and whether or not a large fraction of the mass of the universe is concentrated in unseen elementary particles. There are also practical problems with applying the Standard Model in many situations. We cannot, for instance, accurately calculate the mass of the proton, the various phase transitions that occur in nuclear matter, or even the energy levels and collective properties of nuclei.

The Canadian research programme addresses an important group of these problems. It is well organized and has strong discovery potential at the frontiers of the field. It focusses on three initiatives – participation in the ATLAS experiment at the Large Hadron Collider (LHC) at CERN, the development of the Isotope Separator and Accelerator (ISAC) at TRIUMF, and the Sudbury Neutrino Observatory (SNO). LHC experiments will study matter at the highest energies available, will allow us to explore nature at extremely small scales and will have the potential of finding physics beyond the Standard Model. Canadian scientists, building on their technical expertise and physics interests, are making significant contributions to the ATLAS detector and are poised to play a leading role in the scientific studies that will be performed with ATLAS when the LHC is completed in 2005. The ISAC facility, a very high intensity radioactice beam source, will provide new understanding of important questions in nuclear astrophysics and will use the nucleus as a laboratory to study fundamental forces and symmetries. The Sudbury Neutrino Observatory will measure the flux and energy of neutrinos from the sun and possibly from supernovae. It is a uniquely Canadian project, capitalising on the large store of heavy water available only in Canada, the availability of a very deep mine in Sudbury and the intellectual leadership and imagination of Canadian subatomic physicists. This experiment has the potential to determine neutrino properties beyond the Standard Model and to answer outstanding questions about the energy generation processes in the sun. Canadian scientists have identified a well chosen set of the most important questions in the field, taking advantage of the intellectual and technical resources unique to Canada.

In the near future, most Canadian effort will focus on these initiatives. However, the field is dynamic, and continuously evolves as the research frontiers expand and new ideas are developed. Encouraging other initiatives is essential to maintain diversity within the programme and to allow for future evolution. The field will continue to pursue excellent science, based on the initiative and creativity of Canadians and judged by international peer review.

Subatomic physics is intellectually vital and has enjoyed strong growth over the last decade in Canada. As one specific measure of this, we have identified over thirty young people that have been hired since 1990 in faculty or equivalent positions in this field at Canadian universities. Providing the best possible education for students remains one of the primary goals for university based researchers. Subatomic physics offers unique opportunities to students because it aggressively pushes the limits of technical capability in order to answer very challenging problems. Students also thrive by participating in large international projects and working with elite scientists and students from around the world. This unique education prepares them for achievement at diverse research frontiers, but particularly in subatomic physics. Approximately one quarter of our graduates find academic positions in Canada or abroad, while the remainder move into technical, analytical, or managerial positions in industry where their skills are very much in demand. Although subatomic physicists have used the World Wide Web (a subatomic physics spin-off) in communicating their research to the public, a more coherent public outreach and education programme should be promoted within Canada.

Canadian subatomic physics has an outstanding record of accomplishments. These are detailed in the report. A few of the more recent contributions include precision measurements of the Standard Model parameters at high energies, astrophysical measurements of the rate at which carbon is burned in red giant stars, collective, electromagnetic, and mesonic effects in nuclei, effects of high spin and high temperature on nuclei, and precision nuclear mass measurements. These were accomplished through major Canadian contributions to international collaborations abroad, such as OPAL and ZEUS, and in Canadian laboratories, such as TRIUMF, TASCC and SAL. These accomplishments have earned Canadian subatomic physics a very good international reputation. Many of these projects are still in productive data-taking phases and train young Canadian scientists. However, most of these projects are being brought to completion over the next few years, providing Canada with the resources to confront the questions that will be addressed by ATLAS, ISAC and SNO.

Subatomic physics has also been a major participant to applied and interdisciplinary research. Recent efforts include applications of muons to condensed matter systems and materials, meson and proton cancer therapy, use of special isotopes in positron emission tomography, diagnostic and therapeutic tools in medicine, and the use of neutrons as a tool for material science. Canadian national subatomic physics laboratories have played an active role in promoting such interdisciplinary research and spin-offs, but these efforts should be reinforced by more effective university-based technology transfer programmes.

These achievements have been possible despite a very restrained funding climate. Internationally, the field is experiencing a period of reorganization and intense activity, and there are many possibilities for international collaborations both in Canada and abroad. The extent to which Canadians participate is limited by the availability of resources. However, the Canadian community is committed to setting priorities so that it can contribute significantly to the best projects, as determined by peer review , within the limits set by available resources. The discipline could be helped significantly by more flexibility in the ways in which it can obtain capital funding, by allowing the funding profile to vary to match the rate of construction, and through increased funding.

The Canadian programme in subatomic physics will continue to aggressively pursue excellence.

1 Introduction

Research in subatomic physics addresses some of the most fundamental questions that confront our understanding of nature: What are the building blocks that make up our world? What is the nature of the forces that cause these building blocks to interact, bind and form atomic structure? Canada, with a comprehensive subatomic physics research programme, has made a large intellectual investment in the search for answers to these questions.

The Canadian Association of Physicists (CAP) and Natural Sciences and Engineering Research Council (NSERC) Physics Liaison Committee proposed in February 1996 a wide-ranging review of Canadian academic physics[1] to identify both its strengths and weaknesses, and to provide NSERC and the physics research community with the information to make recommendations that would build on these strengths and address the weaknesses. A research subcommittee was appointed to study those issues relevant to Canadian subatomic physics. Three additional research subcommittees were appointed to evaluate other aspects of the Canadian physics research programme. A Main Committee , consisting of the chairs of the research subcommittees and others, was appointed to coordinate this study and produce a summary report.

This report is the result of the work of the subatomic physics subcommittee.

1.1 Terms of Reference

The subatomic physics subcommittee was given a ten point charge, which we have paraphrased as follows:

1. To survey current and planned academic subatomic physics research.
2. To identify strengths and weaknesses in the Canadian subatomic physics research programme.
3. To identify particular areas of focus for future research, maintaining both diversity and risk-taking to ensure a successful research enterprise.
4. To determine how funding should be distributed to attain the appropriate level of research diversity, focus and risk-taking for the future programme.
5. To evaluate how NSERC can encourage risk-taking, spin-off activities, communication with the public and other scientific disciplines, and interdisciplinary research.
6. To assess interactions and impact with other disciplines.
7. To consider the potential benefits of encouraging major collaborative efforts across subdiscipline boundaries.
8. To consider the impact of 15% increases and decreases in funding.
9. To prepare a preliminary report of the subcommittee's findings, after consultation with the subatomic physics community, and to submit the final report to international reviewers.
10. To synthesize a "Vision Statement" for Canadian subatomic physics.

The complete text of the subcommittee's terms of reference appears in the appendices.

The subcommittee's report will be provided to a set of external reviewers, who will be asked to give written assessments of the scientific quality of the programme. These assessments, together with the reports from all the subcommittees, will provide the basis for further discussion and planning within the Canadian physics community.

We recognise that this report is prepared for several different audiences. First and foremost, it provides the external reviewers with a coherent description of Canadian subatomic physics research, an evaluation of the strengths and weaknesses of the subatomic physic research programme, and addresses the other points in our charge. It will be used by the Main Committee to prepare an Executive Summary that will integrate the conclusions of all four subcommittees. It also is the basis for future consultation between the physics research community, the funding agencies that support subatomic physics in Canada, and the NSERC grant selection committee (GSC) responsible for reviewing and recommending funding for specific subatomic physics projects. Finally, this report provides some of the data that will be used in the next NSERC reallocation exercise[2] to determine future NSERC funding levels for the discipline.

1.2 Methodology

This review is intended to be a community-based discussion of the subatomic physics programme. After appointment of the members of the subcommittee in consultation with the CAP, the Institute for Particle Physics (IPP) and the directors of the Canadian subatomic physics laboratories, the subcommittee held a town meeting at the 1996 CAP Congress and solicited input from the community. At that time, the subcommittee defined in broad terms the manner in which it would achieve its goals.

We distributed an in-depth survey by mail to all NSERC grant-eligible applicants, and by electronic mail to all members of IPP and the CAP Division of Nuclear Physics (DNP). We collected and collated these surveys in October 1996, and have prepared a report summarising the survey responses. Our analysis of the survey forms the basis for many of our conclusions.

The subcommittee met in October 1996 and prepared a draft report that was distributed for comment to the community in December 1996. The final version of this report reflects the consensus of the community's input.

To meet all the objectives of this review, we have included in our report a number of observations to address those issues that we have identified as relevant to our charge. These are addressed to the external reviewers, to the CAP Physics Liaison Committee and to NSERC. They are our response to the issues presented in our charge and are meant to be the basis for further discussion between the research community and NSERC.

We have attempted to address most of the terms of reference of the review in the following sections. However, we have chosen to do so in a way that does not directly relate to the order of the ten items in our charge. To assist the reader in navigating our report, we have included in an appendix a cross reference to the sections of the report where a particular issue is addressed.

The second section of this report recounts the development of subatomic physics in Canada. Section 3 describes the current Canadian subatomic physics research programme. Section 4 discusses training and discipline dynamics, i.e. the evolution of research personnel in the Canadian subatomic physics programme. Issues related to funding, personnel and infrastructure are discussed in Section 5. Interdisciplinary research, risk-taking and diversity are discussed in Section 6. The strengths and weaknesses of the programme identified by the subcommittee are described in Section 7. We conclude the report with our vision of the future of subatomic physics research in Canada.

2 The Development of Canadian Subatomic Physics

The development of subatomic physics in Canada has been driven by Canadian researchers who have excelled in this area at an international level. They have been the intellectual force that has caused the programme to evolve in order to best exploit new physics challenges and to best utilise new facilities and technologies. In particular, the programme has taken advantage of the unique facilities in Canada, such as the TRIUMF laboratory and the SNO facility, to tackle some of the most interesting questions in subatomic physics.

This evolution has been guided by reviews and long range planning exercises. This has given Canada a focussed subatomic physics programme with an appropriate breadth considering the resources of the community. It was also realised early on that there are strong fundamental links between the traditional domains of nuclear, intermediate and high energy physics. This was embodied more than fifteen years ago in a single mechanism to plan, review and fund the whole of subatomic physics in Canada. The flexibility of this approach has proven to be advantageous, as it has strengthened the intellectual links and has allowed the programme to respond more effectively to new initiatives in each of the traditional domains. An implication of this approach is that the future success of subatomic physics in Canada depends on all the various facets doing well, unlike other countries where efforts in each subdiscipline are largely independent of each other.

Overall, there are approximately 245 subatomic physicists in Canada today,[1] of which approximately 85 are involved in theoretical subatomic physics, 70 are involved in low and intermediate energy experiments, 70 are involved in particle physics experiments, and 20 are involved in the Sudbury Neutrino Observatory (SNO).

2.1 Low and Intermediate Energy Programme

Subatomic physics emerged as a major area of research in Canada in the forties, in large part due to a major investment in the nuclear reactor development effort. The research programme expanded to thirteen laboratories based at Canadian universities, with Van de Graaf and tandem accelerators, cyclotrons, a linear electron accelerator and a reactor. Chalk River Laboratories (CRL) had the most advanced facilities that included a tandem accelerator and two large research reactors. Condensed matter physics was the beneficiary of the large flux of thermal neutrons available at the Chalk River reactors, as neutron scattering became an important tool in the study of materials. This was one of the first interdisciplinary applications of subatomic physics, and led to the 1994 Nobel Prize in Physics being awarded to Prof. Brockhouse of McMaster University.

In 1966 a coalition of government and research funding agencies provided the initial support for the construction of TRIUMF (Tri-University Meson Facility) on the University of British Columbia campus. Initial funding for the construction of TRIUMF was provided in 1968 and first beam was available in 1974. The center of this facility is a 500 MeV proton (H^- ion) cyclotron with a peak current of $\sim 200\ \mu$A. It quickly developed an active research programme in strong and weak interaction physics, and has been used extensively by national and international research groups. Experiments at TRIUMF have had significant international scientific impact, with one of the most

[1] These data come from 1996 NSERC statistics, and represent the number of researchers who hold a faculty appointment in a Canadian university (or are research scientists) and are eligible to apply for NSERC research grants.

recent advances being the results of the "Red Giant" experiment, which provided the first tight constraint on the measurements of an important astrophysical nuclear reaction. The muon beams available at TRIUMF have been used to establish muon spin rotation (μSR) as an effective technique for the study of materials and chemical reactions.

By the late seventies, the physics of nuclei was increasingly being viewed from a different perspective, incorporating the unification of the electromagnetic and weak interactions, the view that nuclei consisted of quarks, and the theory of the strong interactions known as Quantum Chromodynamics (QCD). Many of the existing facilities needed to be updated or replaced, and a consortium of eastern universities with CRL began to plan for a new Canadian research facility. In response to this, Atomic Energy Canada Ltd. (AECL) built a superconducting cyclotron for heavy ions and attached it to their existing tandem accelerator at CRL. This project, known as the Tandem Accelerator Superconducting Cyclotron at Chalk River (TASCC), was carried out by AECL accelerator physicists and technicians and the facility became fully operational in 1991. TASCC has developed an international reputation for its ground-breaking measurements of the structure of highly-excited nuclei and their decay to lower energy states.

Much of the remaining low energy programme was based at the Saskatchewan Accelerator Laboratory (SAL), an electron accelerator with a maximum energy of 300 MeV located at the University of Saskatchewan. This facility was upgraded by NSERC in the early eighties to a continuous electron beam accelerator (100% duty factor machine), greatly enhancing its ability to explore nuclear properties sensitive to the electromagnetic "probe" provided by the electron.

The Canadian research effort has also been influenced by new opportunities that arose outside the country. The decision by the United States to build the Relativistic Heavy Ion Collider (RHIC) and the Continuous Electron Beam Accelerator Facility (formerly CEBAF and now known as the Thomas Jefferson National Accelerator Facility or Jefferson Lab) has attracted several groups in Canada to pursue research at these facilities. This offshore effort in intermediate energy physics is becoming increasingly important as the number of Canadian facilities declines. Canadian subatomic physicists have also been involved in many smaller scale studies (such as neutrinoless double-β decay, for example).

Overall reductions in basic research funding in Canada and the need to direct resources toward the very highest priority elements of the subatomic physics programme have resulted in decisions to shut down several facilities. NSERC subatomic physics funding for SAL exists only until 1998, although a proposal to convert it into a synchotron light source is under active consideration. Independently, AECL has decided that it can no longer continue support of a basic nuclear physics research programme at CRL and has closed down TASCC. This is forcing the relocation of several state-of-the-art instruments to offshore facilities and a redirection of the Canadian research effort based around these devices (some of these detectors may relocate to TRIUMF once a new radioactive beam facility becomes operational).

TRIUMF now remains the only national subatomic physics research facility in Canada. However, with the approval of a five year funding plan in 1995, TRIUMF has embarked on the development of an exciting new research facility known as ISAC (Isotope Separator and Accelerator), which will produce and accelerate high intensity beams of radioactive isotopes. This facility, due to become operational with low energy beams in 1999, is expected to make unsurpassed measurements of astrophysical reaction rates and nuclear structure.

The TRIUMF five year plan also includes funding for a Canadian contribution to the Large

Hadron Collider (LHC) at CERN, Geneva, and for infrastructure support for offshore subatomic physics experiments. The contribution to the LHC has provided Canadian researchers access to this premier facility where new discoveries are very likely to occur.

The subatomic physics community has made the best use of its opportunities to contribute to some of the most significant physics projects in the last five decades while recognising the need to shed projects with lower scientific priority. This is most apparent in the last several years, but has always been an element of the Canadian subatomic physics programme.

2.2 Particle Physics Programme

The programme in particle physics was initiated in the sixties with numerous experiments in the United States utilising the accelerator facilities available at Argonne National Laboratory, Brookhaven National Laboratory, the Fermi National Accelerator Center (FNAL or Fermilab) and the Stanford Linear Accelerator Center (SLAC). The Institute of Particle Physics (IPP) was formed by the research community in 1971 to coordinate particle physics research in Canada. This unique organisation continues its coordination role today, and provides significant infrastructure support to Canadian particle physics.

The early work at US facilities was followed in the eighties by extensive collaborations on European projects. The first major European involvement of Canadian particle physicists was with the ARGUS experiment at DORIS, Germany, an e^+e^- collider designed to study B mesons. A large group of Canadian investigators also proposed and received funding to make a major contribution to the OPAL detector at LEP I, a new e^+e^- collider under construction at CERN. This programme was funded jointly by NRC and NSERC in 1982.

Scientific interest in very high energy electron-proton colliders was sparked by the discovery of quarks inside nuclei in the seventies. Canadian physicists responded to this in 1979 by proposing an e^-p collider at Fermilab with the electron machine funded by Canada. Although this proposal was not approved, Canadian researchers were subsequently successful in obtaining funding for contributions to the HERA e^-p collider at DESY and to the construction of the ZEUS detector.

The participation in LEP I has led to a continuing effort at LEP II with the OPAL detector. With the CERN decision to proceed with the construction of the Large Hadron Collider (LHC), Canadian researchers have obtained commitments from the government to make contributions to the construction of LHC. There is now a strong commitment to the physics of the LHC and Canadian researchers are making a significant contribution to the ATLAS detector.

A smaller new initiative in particle physics has recently been initiated at SLAC, where an e^+e^- collider is being upgraded to become a "B factory," a facility that will produce copious numbers of B mesons. The primary focus of this project is to understand charge-parity (CP) violation in the b quark sector. CP violation is believed to be the reason why our universe is dominated by matter with very little antimatter. Canadian investigators have been funded to assist in the BaBar detector construction and in the subsequent physics studies.

2.3 The Sudbury Neutrino Observatory

In keeping with the philosophy of pursuing excellent research and capitalising on the unique strengths of the subatomic physics in Canada, a unique facility, the Sudbury Neutrino Observatory

(SNO), was proposed to the Canadian government in the late eighties. This facility is designed to address what has become known as the "solar neutrino problem:" the apparent flux of neutrinos from the sun is significantly less than expected. This observation is in direct contradiction with the expected rate based on detailed solar model calculations, and presents one of the deepest mysteries in subatomic physics today. The decision to build this facility, with contributions from funding agencies in the United States and the United Kingdom, was made in 1990 and the facility is now nearing completion.

It utilises heavy water placed deep in the Sudbury INCO Creighton nickel mine as the detection medium for the neutrinos. It is expected that the facility will start taking data in 1998. This programme involves a large group of Canadian researchers and is currently the most visible, uniquely Canadian project in subatomic physics.

2.4 Long Range Planning in Subatomic Physics

The subatomic physics community has over the last decade recognised the need for long range planning in order to optimise the effectiveness of the research programme. Since 1988, three long range planning exercises have been completed, and the recommendations that have arisen from these reviews have shaped the future of the discipline.

The latest long range planning review was conducted in 1995. NSERC appointed an Advisory Committee for Subatomic Physics to establish priorities in the field in view of the numerous opportunities to participate in experiments with exciting physics implications, yet in a scenario with limited funds. At the time, it was known that the Canadian government had decided to provide support to TRIUMF to construct ISAC and to make a contribution to the construction of the LHC. The committee, chaired by Professor Brock Fenton of York University, recommended that in a scenario with an increase in NSERC funding of 15%, the priority of the programme should be the ATLAS, ISAC and SNO initiatives. In a pessimistic scenario with a funding decrease of 15%, participation in ATLAS would not be possible. In the scenario of static funding, even with the phase-out of SAL, it would not be possible to participate in a second proposed particle physics project (the BaBar experiment) and there would be barely enough resources to support ATLAS with a delayed funding profile. In all scenarios, funding for university research at TASCC was recommended to remain approximately constant. The resulting "Fenton report" has defined the direction of subatomic physics for the next few years[3].

In response to overall reductions made by the Canadian government in 1995, the funding "envelope" for subatomic physics was set at a level that corresponded approximately to the static funding scenario contemplated in the Fenton report. The NSERC GSC has subsequently followed most of the programme recommendations contained in the Fenton report. The most notable departures from the report have been the decisions to fund the BaBar experiment, though in a more limited manner than had been initially proposed, and to give SAL the same amount of funding but over a two year funding profile instead of the recommended three year plan. More recently, the AECL decision to close the TASCC facility in order to accommodate further federal funding cuts has required further adjustments to the Fenton plan.

2.5 Summary

The objective of providing this historical perspective is to illustrate the evolution of subatomic physics in Canada and the community's ability to remain at the research frontier. Although, the specific long term goals have changed distinctly with time, the focus of the programme has remained on the pursuit of excellence in basic research. This is essential for the long-term intellectual health of the field in Canada. The evolution of the programme is strong testimony to the vitality of a field that has been maintained, nurtured and advanced over five decades. It also makes us confident that the future programme will carry on this tradition of exciting research at the frontiers of our understanding of nature.

3 The SAP Programme

3.1 Overview

3.1.1 The Fundamental Questions

Subatomic physics is the study of the fundamental constituents of matter and their interactions. The most widely accepted picture of the evolution of our universe predicts a definite sequence of events. Very soon after the primordial "Big Bang," the universe was in a regime where "free" quarks, leptons, photons, gluons and other force carriers co-existed at high temperature. As the universe expanded and cooled, it entered a regime where these objects formed protons and neutrons, which in turn formed nuclei, atoms and molecules.

This paradigm assumes that all matter consists of three "generations" of quarks (which constitute atomic nuclei) and leptons (such as the electron or muon), with each generation consisting of a pair of related particles. These particles interact via four fundamental interactions, the electromagnetic force, the weak force, the strong force and gravity. These forces are mediated by force-carriers: the photon in the case of the electromagnetic force, the W^+ and Z° bosons for the weak force, the gluons for the strong force and the gravitons for the gravitational force. This theory, known as the Standard Model, forms the theoretical basis for almost all work in subatomic physics. Although consistent with current experimental data, the Standard Model predicts a number of phenomena that we have not observed. It also depends on almost two dozen parameters whose values are constrained by data, but are not predicted by the model.

At the most fundamental level, there remain questions about the three generations of quarks and leptons. The discovery of the top quark in 1995 has been greatly satisfying, as its existence was a long-standing, unverified prediction of the Standard Model. However, we are still trying to understand the mechanism that generates mass and why there is such a preponderance of matter over anti-matter in our universe. We recognise that the Standard Model is not the final answer to these fundamental questions.

The underlying unification of the weak, electromagnetic and strong interactions raises the question about theories that go beyond these ideas. Various theories that extend the Standard Model to account for differences in these forces predict a variety of phenomena, and much of the current work in subatomic physics is motivated by searching for these hypothetical effects. More sensitive searches for such phenomena require that we study particle interactions at much higher energies. The energy frontier must be extended if we wish to probe further beyond the Standard Model. In addition, well-chosen high precision studies at lower energies also allow us to explore this high-energy frontier though in an indirect manner.

However, the high energy regime is not the only frontier in subatomic physics. Our understanding of lower energy effects is far from complete, ranging from our inability to understand the behaviour of even pairs of quarks at low energies (what is known as non-perturbative QCD) to the complex interactions that many-body nuclear systems exhibit. Particle astrophysics represents yet another frontier as it attempts to unify our understanding of particle interactions with our observations of the cosmos.

There is a large number of lower-energy phenomena that are simply not well-understood. The existence of a free "plasma" of quarks and gluons has not been verified and its properties are not known. There are questions about the many-body systems that appear as isotopes of various nuclei. The properties and behaviour of nuclear systems as their temperatures increase are not known. The shape deformations caused when large angular momentum is transferred to nuclei are not completely understood. We do not have a detailed understanding of the confinement of the quarks and gluons into hadrons. Do quarks show up by deconfinement of baryons through an increase of temperature and/or density? Is there an unusual transition region where baryons, mesons, quarks and gluons co-exist? What are the important properties of such a mixture? It is the collective behaviour of such systems that provides new excitement and new insight into the properties of nuclear matter. Even though such aspects of nuclear many-body systems are rather distinct from the fundamental questions discussed earlier there is a close linkage through the presence of strong interactions among baryons.

The study of subatomic physics is closely linked with the cosmological development of stars, novae and supernovae. Hadrons are still being "cooked" into nuclei in the interior of stars, but the stellar nuclear reactions that are making these new elements involve a very large number of nuclei for which little is known of their properties. What we do know is derived from a limited set of stable or near stable nuclei on earth. Many of the nuclear reactions that occur in stars involve nuclei that are far removed from these stable isotopes and therefore can only be studied at laboratories such as TRIUMF-ISAC.

The Standard Model not only links the development of the universe from the Big Bang to the present day, it also forms the basis of our understanding of stars such as the sun. Studies of the neutrino flux from the sun have given us a better understanding of its interior, but this is one of the areas where there is a clear discrepancy between observation and our theoretical models. More detailed and sophisticated measurements are needed to better understand the temperature and density profiles associated with the stellar furnace.

It is this broad perspective, ranging from the subnuclear world to the cosmos, that defines the essence of subatomic physics and knits it together into a single field of research. The diversity of the research programme that it engenders is a reflection of the unique talents and imagination of the individual researchers who participate in subatomic physics. Allowing sufficient diversity is therefore important if Canada is to tap into the full intellectual resource represented by Canadian subatomic physicists.

3.1.2 Subatomic Physics Projects

Success in experimental subatomic physics requires access to sophisticated and costly facilities that can only be supported on an international scale. The limited access to these facilities, the cost involved in operating them, and the difficulty of performing some of the experiments require that most investigators work collaboratively on the same project or a set of closely related studies.

It is therefore natural to pose the question of how one can measure the impact of Canadian researchers in this field where the number of Canadian researchers on an international project may range from a few percent to half or more of the collaboration. The answer lies in evaluating the impact that the individual investigators make with their intellectual and technical contributions. This is often recognised by having Canadians rise to prominent roles within a given collaboration. Such influence can be seen in almost all of the large subatomic physics projects that Canada is involved in. Examples of such contributions can be seen in the SNO collaboration (where Canadian scientists constitute the majority and a Canadian is the project spokesperson), the ZEUS and HERMES collaborations (where Canadians have served as deputy spokespersons), in the OPAL collaboration (Canadians have served as overall physics analysis coordinators and have led the studies of the τ lepton), in the CDF collaboration (where a Canadian has been the top search coordinator and led the software development effort) and in the search for rare K meson decays underway at the Brookhaven National Laboratory (where Canadians have been leaders of the project from its inception). Canada has also made outstanding technical contributions to the design and construction of experiments and specific detectors. More detailed descriptions of the most recent contributions can be found in the following subsections.

Canadian subatomic physics also encompasses studies that are done with smaller teams, many of which consist of entirely national researchers. In these cases, it is easier to identify and measure the impact of Canadians. Canada has taken a leading role in the study of heavy ion interactions, using the accelerator facilities at CRL to study the structure of very heavily deformed nuclei. Canadian scientists have played a leading role in the studies of nuclear systems interacting with low energy pion and electron beams, with facilities at TRIUMF and SAL dedicated to these experiments.

3.2 Recent Canadian Accomplishments in Subatomic Physics

In the course of this study, we were able to identify many (though not all) of the seminal contributions Canadians have made to the field of subatomic physics. The list is impressive:

- Precision measurements of electroweak processes, strong interactions and many of the fundamental parameters of the theory (OPAL at CERN).
- Physics at unprecedented short distances (ZEUS at HERA).
- Search for extensions to the Standard Model in the rare decay of K mesons (Brookhaven National Laboratory).
- Structure of the neutrons and protons (ZEUS and HERMES at HERA).
- Discovery of the sixth (top) quark (CDF at Fermilab).
- Measurements of the rate at which carbon is converted to oxygen in red giant stars (TRIUMF).
- Precision measurements of meson decays (TRIUMF).
- Interactions of mesons and nucleons with nuclei, leading to a better understanding of their role in nuclear structure (TRIUMF).
- Measurements of the mixing of electroweak and strong interactions at low energies using the radiative capture of pions and muons (TRIUMF).
- Collective properties of nuclei (TRIUMF and TASCC).
- Applied and inderdisciplinary research, including applications of muons to condensed matter systems and materials, meson and proton therapy for cancer, the use of isotopes in Positron Emission Tomography (PET), and other diagnostic methods (TRIUMF).

- Understanding of the state of a nuclear stystem when it is rotated at very high speeds and heated to extreme temperature (TASCC at CRL).
- Techniques to perform precision mass measurements of unstable nuclei and weak nuclear transitions (CRL).
- Use of neutrons as a practical tool for material science (CRL).
- Study of strong interactions at low energies with medium energy photons (SAL).
- Precision measurements of electromagnetic interactions with nuclear systems (SAL).

We elaborate on these items in the following subsections, but bring them together here to demonstrate that Canadians are not only active in subatomic physics, they have had a marked impact on their field at an international level and they are recognised for their contributions to the advancement of the science and technology associated with it.

This physics programme is an exciting one that continues to attract some of the best young people. However, higher recognition and support within Canada is essential to maintaining a healthy discipline. We believe the future of this discipline can and should be judged on a global scale. Although decisions about the development of new facilities now must be done in an international context, Canadian researchers can continue to play a leading role in setting the research priorities provided that they have the resources to be able to define and select the best scientific opportunities and to participate fully in those projects.

3.2.1 Section Overview

The remainder of this section deals with the work being carried out by researchers from Canada at various laboratories in and outside Canada. The programme has a direct focus on some of the most interesting problems intellectually. At the same time, it has the diversity to support a wide range of investigations dealing with nuclei, reactions of interest in astrophysics, quark-gluon plasma, fundamental properties within the Standard Model and finally extensions to ideas that are still in a formative stage.

The Canadian subatomic physics community is not large enough to tackle all of the interesting and important questions in subatomic physics. Instead the community has chosen to select a range of topics and approaches consistent with the resources and expertise that exist in Canada. Strong programmes have been built around several unique Canadian facilities such as TRIUMF, TASCC and SAL, and around excellent researchers collaborating at offshore facilities.

We first describe the new initiatives that represent our future programme: SNO, ATLAS and ISAC. SNO is the highest priority experiment of the Canadian programme and is expected to begin taking data within the next year. It is an excellent example of an experiment that utilises nuclear physics techniques to shed light on the reactions in the sun and fundamental properties of the neutrino. The ATLAS experiment, given very high priority in the Fenton report, is the future focus of the particle physics programme. The ATLAS experiment will put Canadian scientists at the highest energy frontier, and represents a natural progression from the Canadian involvement on the UA1, UA2 and CDF experiments. ATLAS will investigate the manner in which the Standard Model goes about explaining how different particles have mass. An understanding of the origin of mass is believed to be one of the keys to making progress beyond the Standard Model. Canada is also making a contribution to the construction of the LHC through the TRIUMF laboratory. TRIUMF is presently constructing ISAC, a new high intensity radioactive beam facility. These beams will be a major research tool for astrophysics, particle physics and nuclear structure studies well into the next century.

We then describe the existing programme, briefly highlighting the Canadian contributions and accomplishments. The present particle physics programme is focussed on two large efforts, OPAL and ZEUS. Canadian researchers are also involved in three other ongoing particle physics experiments, HERMES, the rare K^+ decay experiment E787 and CDF. The nuclear physics programme is centred at SAL, TASCC and TRIUMF. The Canadian contributions to "offshore" experiments at RHIC, Jefferson Lab, Ganil and Gammasphere will also be described.

Finally, we will describe the programme of Canadian theoretical subatomic physics. This is a very important part of the Canadian research effort and includes some of the most talented Canadian researchers. Despite the modest level of funding for theoretical subatomic physics (about 10% of the total funding of subatomic physics by NSERC), it has remained reasonably well matched to the experimental programme.

3.3 The Future Canadian Subatomic Physics Programme

The Canadian subatomic physics community is focussed on three major new initiatives: the Sudbury Neutrino Observatory, the ATLAS experiment at the LHC, and the ISAC radioactive beam facility at TRIUMF. These have been identified as the highest priority projects within the community and are expected to involve over half of the scientific effort.

However, in order to maintain a sufficiently diverse programme that can address the frontiers of subatomic physics, the community is involved in several other initiatives. The BaBar experiment, which will search for evidence of CP violation in bottom mesons, already has received capital and operating funds to support a modest Canadian effort. A proposal has also been made for a new experiment at TRIUMF to measure muon decay to very high precision, and this is expected to become the focus of the non-ISAC programme at TRIUMF. There is interest in studying the rare decays of neutral K mesons, as a natural extension to the rare decays of charged K mesons that Canadians have taken a lead role in. Finally, a number of intermediate energy experiments are underway or are in the proposal stage. These include participation in ongoing and planned experiments at Jefferson Lab, and ongoing participation in an experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Although it is not possible to identify all of the new initiatives that will be proposed in future years, it is very important to the field that sufficient resources be available to support these more modest investigations.

3.3.1 The Sudbury Neutrino Observatory

Previous experiments measuring solar neutrino fluxes (Homestake, Kamiokande, GALLEX and SAGE) all report rates that are significantly lower than expected. It is difficult to reconcile the detected numbers of neutrinos with any solar model that matches other observed properties of the sun. A consistent picture can be developed if we assume that neutrinos can change flavour either during passage through the sun or in vacuum. However, this explanation is not conclusive as it still depends on the use of solar model data to fix initial fluxes.

The Sudbury Neutrino Observatory is designed to address these fundamental questions associated with neutrinos. With heavy water (D_2O), SNO can measure the number of electron neutrinos (ν_e) reaching the earth as well as the total flux of all neutrino types. This will definitely test the hypothesis that neutrinos change "flavour" (eg., convert from electron neutrinos to muon neutrinos) on their way from the sun to the earth. These measurements will also provide a measure of the total electron neutrino flux from the sun, testing the validity of the standard solar models. The results from other experiments since 1990 have strengthened the importance of the measurements that can be made with SNO. The potential impact on particle physics and astrophysics is substantial.

SNO is a 1000 ton heavy water Cerenkov detector, located at the 6800 foot level of the INCO Creighton Mine, near Sudbury, Ontario. Neutrinos are observed by their interactions with the heavy water molecules that produce Cerenkov light. This light is detected by an array of almost 10 000 counters immersed in a light water shield that surrounds the heavy water vessel. A schematic view of the detector is shown in Fig. 1. It has been built by a collaboration of Canadian, US, and British scientists. Canada has contributed roughly 75% of the funding for SNO, and the project has very significant international visibility and support. Canadian scientists are responsible for a large fraction of the detector, including the heavy water acrylic vessel and its suspension system, the heavy and light water purification systems, various components of the readout systems, calibration systems, the experimental control systems and the management of the facility. The heavy water, valued at approximately $300M, is on loan from AECL.

The large Canadian collaboration involved in SNO, its location in Canada, the large Canadian investment in the detector, and its scientific importance led the Advisory Committee for Subatomic Physics in 1995 to label this project as "the highest priority subatomic science activity in Canada."

The Observatory is scheduled to be filled with heavy water and light water shielding starting in early 1998. The contract with AECL provides for the heavy water to be available until the year 2001. Assuming return at that time, it is planned to operate the detector for a further two years with light water to obtain a fuller understanding of radioactive backgrounds.

The SNO detector will have a broad range of physics and astrophysics capabilities, with the primary focus on the detection of solar neutrinos. SNO will detect electron neutrinos and all neutrino types separately, with relatively high rate ($\sim$ 3000 per year), with good energy resolution and with directional sensitivity. This set of capabilities is unique for understanding solar neutrinos.

The most important feature of the SNO detector is the use of heavy water as a detection medium. Neutrinos interact with the heavy water in three distinct ways. The total flux of all neutrino types can be measured by the neutral current (NC) reaction, the electron neutrino flux and energy spectrum can be measured with the charged current (CC) reaction, and electron scattering (ES), with its smaller cross section, can be used to check consistency and give directional information. The combination of measurements can provide definitive measurement of neutrino oscillations independent of the solar model. Such effects can either be matter-enhanced oscillations in the sun (the MSW effect) or vacuum oscillations; the shape of the energy spectrum allows better measurement of the oscillation parameters and tests whether the parameters suggested by previous experiments are correct. The relatively high counting rate will allow searches for other effects:

1. Regeneration in the earth if electron neutrinos have changed flavour. This results in a day to

Figure 1: A schematic view of the Sudbury Neutrino Observatory.

night neutrino flux difference and energy dependence.

2. Seasonal variations in flux indicative of vacuum oscillations (due to the variation in earth-sun distance resulting from the eccentricity of the earth orbit).

3. Variations with season or solar cycle correlations that could arise, for example, from the coupling of solar magnetic fields to a finite neutrino magnetic moment.

With these capabilities, the SNO experiment is unique among present and future experiments. The observation of anomalies via any of the three categories provides evidence of neutrino properties outside the Standard Model. The combination of measurements enables the identification of the mixing parameters and the specific determination of flavour change.

SNO will also have the capability of making several other measurements. It will be able to detect the ν_μ and ν_τ neutrinos from galactic supernovae and determine neutrino masses to values as low as 30 eV$/c^2$. The detector will be able to measure the flavour composition of the atmospheric neutrino flux, including separate ν_μ and ν_e rates. It will be sensitive to signatures from "relic" neutrinos from past supernovae. Finally, SNO can be used to search for dark matter, nucleon decay and neutron-antineutron transitions in deuterium.

The scientific motivation for SNO is now stronger than when the project was started. With the experiment readying to take data in the next year, it is receiving substantial international attention for its discovery potential in the fields of subatomic physics and astrophysics.

3.3.2 High Energy Physics

Studies at the Next Energy Frontier with ATLAS

The LHC will be a proton-proton collider designed to collide protons together with a maximum energy of 14 TeV. This represents an increase of almost an order of magnitude over the energy regime accessible to the Fermilab Tevatron. This dramatic increase in energy combined with very high luminosity (the rate at which proton collisions will occur) allows LHC experiments to make a detailed investigation of the phenomena associated with the origin of mass. Technically, this is known in the Standard Model as electroweak symmetry breaking, and is a fundamental constituent of the theory, involving the existence of a new type of particle known as the Higgs boson.

In all likelihood, an LHC experiment will be able to determine that the Higgs boson is the mechanism by which particle masses are generated. There are good reasons to believe that either the Higgs boson predicted by the Standard Model will be observed, or new phenomena will occur that will play a similar role. Since the Standard Model is not a complete description of nature at the most fundamental level, the general-purpose detectors at the LHC will carry out the detailed investigations necessary to understand these new phenomena. The most exciting possibility is that the real mechanism of electroweak symmetry breaking is unexpected, and that experimentation at this energy scale will reveal completely new phenomena. The LHC is the only facility which will be able to address these questions in the foreseeable future. As such, the LHC machine and its detectors will be the premier subatomic physics discovery instruments well into the next century.

A Canadian group is involved in the ATLAS collaboration, one of the two approved LHC experiments. The ATLAS collaboration consists of 1500 physicists and engineers from 140 institutions from around around the world. They are designing, testing and constructing the world's largest toroidal detector. The Canadian ATLAS collaboration comprises 33 physicists and over two dozen engineers and technicians that are involved in a coherent and critical mass effort within the framework of the ATLAS collaboration. The ATLAS/Canada group has the size and experience to face the challenges presented by the construction of ATLAS. These physicists are supported by considerable technical resources at TRIUMF, CRPP and various universities. Canadians constitute approximately 4% of this collaboration.

ATLAS/Canada has taken responsibility for detector elements that are of central importance to the experiment. Canadian researchers are involved in two closely related projects; the liquid argon hadronic endcap calorimeters and the forward calorimeters. The groups involved in the hadronic endcap project are the Universities of Alberta, Carleton and Victoria, CRPP and TRIUMF. Those working on the forward calorimeters are the Universities of British Columbia, Carleton and Toronto, and CRPP. Both of these calorimeter systems, shown in Fig. 2, are contained within the same cryogenic volume and form a single integrated mechanical system, with many mechanical design problems in common. Apart from the mechanical design there are also many shared R&D

Figure 2: A isometric view of the ATLAS central, endcap and forward calorimeter systems. Canada is constructing half of the endcap hadronic calorimeters and half of the forward calorimeters.

problems. The Canadian groups have taken a common approach to investigating the important issues of materials certification for cryogenic behaviour and influence on liquid argon purity, and the behaviour of materials under intense radiation. These studies are led by the group at the Université de Montréal.

Due to the short interaction time between possible proton-proton collisions (25 ns), the ATLAS detector requires very fast, parallel electronics for its readout and trigger systems. The University of Alberta group has developed a switched capacitor analog pipeline for use in the calorimeter system. Growing out of this work, the group has redirected its efforts towards the controller system for the calorimeter readout. Recently the group has been one of the four groups (Alberta, Nevis, Orsay, and Saclay) given responsibility for the development of the final calorimeter readout system.

The ATLAS/Canada collaboration received funding for capital construction of $12.2M dollars in April 1997 and has now embarked on the construction project this represents. These detector subsystems have to be ready rather early in the full detector assembly so that most of the construction will be performed in the next five years. The scale of this capital commitment is consistent with that recommended in the Fenton report.

ATLAS/Canada has been involved from the start in detector simulation and physics analysis studies. The group works together sharing ideas, software and results. The Canadian studies have concentrated on detector and physics issues that particularly relate to their hardware responsibilities – the hadronic liquid Argon Calorimetry in the endcap and forward regions. The particular areas where Canada has been making a coherent impact are studies of the effects of the "pileup" of multiple interactions in one beam crossing, jet resolution studies, and heavy Higgs searches.

Members of the ATLAS/Canada collaboration have been active in the international collaboration since its inception, and they play an integral role in the management of the collaboration. They have achieved a level of recognition within the community that has allowed them to successfully propose taking responsibility for important components of the ATLAS detector. During the past year, the Canadian group has developed and finalised its responsibilities for the detector construction (as described above). The group will spend much of the next eight years constructing the proposed detector components, installing and commissioning them. The reward for this rather lengthy construction phase will be found in the data-taking and physics analysis phase that will follow.

Bottom Physics at BABAR

Canadian subatomic physicists have focussed on the physics of bottom quarks, going back to the ARGUS experiment in the mid-eighties and the more recent OPAL, CDF and CLEO II experiments. One of the most important open questions in particle physics, the origin of CP violation, can best be addressed by very precise, high statistics studies of bottom meson (B) decays, which are particularly sensitive to CP violation effects. CP violation provides the mechanism by which the observed preponderance of matter over antimatter can be understood. A Canadian proposal to participate in the BaBar experiment, designed to address this issue, was funded in April 1996.

The new high luminosity PEP II B-Factory is under construction at SLAC and a large international collaboration has formed to carry out the single experiment, called BaBar. The primary goal of the BaBar experiment is to investigate the nature of CP violation within the bottom quark system. These measurements will give a definitive test of the model of CP violation as it is presently accommodated in the Standard Model. A wide variety of other B meson, charmed hadron, τ and $\gamma\gamma$ physics studies will also be carried out. The experiment is based on tagging one of the two B mesons produced in the e^+e^- annihilation and full reconstruction of the second B meson using many different B decay modes. The asymmetric beam energies will allow a measurement of the difference in decay times of the two B mesons, and hence a measurement of the interference effects due to CP violation.

The BaBar detector construction has a very tight schedule; it must be completed within the next two years to be ready for physics in mid-1999. The Canadian group has been very active in BaBar from its inception. They have contributed significantly to the design of the central tracking drift chamber, and have taken responsibility to assemble the chamber at TRIUMF as Canada's BaBar contribution. The Canadian effort also includes work on the chamber readout electronics and the online controls systems.

3.3.3 ISAC and Research with Radioactive Beams

Nuclear physics, the study of many body systems of nuclei, has been limited in part by the availability of beams of stable or long-lived isotopes. Of the 7000 stable nuclei that are predicted to exist, only a small fraction of the 263 stable and long-lived ones can be produced and accelerated into particle beams. The studies of the systematic behaviour of a limited sample of nuclei has led to models that have been successful in describing the nuclei near what is called the "line of stability." When these models are used to determine the properties of nuclei far from the line of stability, they provide unreliable predictions. Yet the field of nuclear astrophysics needs this information, since the full range of isotopes is involved in many astrophysical processes. An example of this is the energy generation in stars like the sun, novae, supernovae and in the x-ray and gamma emitters. The isotope abundances observed in our universe at different locations (for example, the earth, moon and meteorites) is related to the nucleosynthesis that occurred since the "Big Bang" and is continuing in stars. Properties of these stellar objects are directly related to isotope formation and processing.

Because of the conditions that exist in stars and other astrophysical objects, dramatic changes in behaviour can occur due to rare nuclear reactions or relatively small changes in reaction rates. Consequently, very large numbers of radioactive isotopes are required in order to make meaningful measurements of these rare reactions. During the last ten years, it has become possible to generate a wider range of radioactive beams. Recent advances in accelerator technologies, the development of better ion sources and the availability of high intensity beams have led to the realisation that high intensity radioactive beams of unstable isotopes can be generated. In several countries around the world, radioactive nuclear beam facilities are now operating, are being built or are in the planning stages. Canada is entering this new field with a very powerful and versatile facility known as ISAC (Isotope Separator and Accelerator), located at TRIUMF. This initiative builds on the very successful TISOL (Test Isotope Separator OnLine) facility developed at TRIUMF.

The high proton intensities of the TRIUMF cyclotron are used to produce isotopes and separate them into pure beams using the ISOL technique developed at CERN (ISOLDE) and tested at TRIUMF with the TISOL facility. The proton beam energy and intensity will produce the most intense source in the world for the near future. A complex of accelerators based on an RFQ linac and a room temperature CW linac will bring the ion beam energies to 1.5 MeV/nucleon, in the range of thermonuclear reactions in stars. Plans for raising the energy to tens of MeV/nucleon are being considered. The facility will operate with low energy beams (~ 60 keV/nucleon) in the spring of 1999 and the accelerated beams will be available early in 2000.

The scientific programme of ISAC will encompass a broad range of activities in nuclear physics, nuclear astrophysics, symmetry tests, nuclear reactions, nuclear structure, material science and nuclear medicine. The main focus of the Canadian physicists planning to use ISAC is nuclear astrophysics, more specifically the measurement of key reaction rates for proton and alpha radiative capture on exotic unstable nuclei. Typical examples of these are the reactions $^{19}\mathrm{Ne}(p,\gamma)$, $^{15}\mathrm{O}(\alpha,\gamma)$ and $^{7}\mathrm{Be}(p,\gamma)$. The first two reactions are critical in understanding the evolution of stars via the processing of carbon, nitrogen and oxygen at high temperature ($\sim 10^9$ C) –referred to as the hot CNO cycle–and the break-out path from the CNO cycle to higher elements. The latter reaction controls the number of high energy neutrinos emitted from the sun. The higher energy beam programme will also make possible the detailed study of the properties and structure of nuclei.

Exploitation of the recently developed trapping techniques for neutral atoms will allow a new look at nuclear beta decay correlations. These can set limits or shed light on possible extensions of the Standard Model (for example, right handed currents and scalar interactions). Mass measurements of nuclei far from the line of stability are needed to allow reliable extrapolation to nuclei at the far end of isotopic chains. Energetics for many reactions are also the determining factor in the evolution of stars. These measurements will be made using a state-of-the-art neutral atom trap known as TRINAT.

Condensed matter research will make use of polarised ^{8}Li beams and the techniques developed for the current muon spin resonance (μSR) programme at TRIUMF to study, for example, interfaces and thin film magnetism. A nuclear orientation refrigerator will be available for magnetism, nuclear correlation, and time reversal invariance studies.

Pure isotopes in large quantities will also be available for medical research opening new opportunities for their use as imaging agents or in therapies.

3.3.4 Low and Intermediate Energy Physics

Although ISAC is expected to be the highest-priority physics experiment at TRIUMF, the traditional non-ISAC programme is expected to continue in the future. Perhaps the most exciting future project is a proposed experiment to measure to unprecedented precision ($\sim 10^{-4}$) the parameters describing the Michel spectrum in μ decay, i.e. the energy distribution of the positrons in the decay $\mu^+ \to e^+ \nu_\mu \nu_e$. This measurement will be a very sensitive test for effects in the electroweak interaction that are not predicted by the Standard Model. The goal is to get information on left-right symmetric models and the sensitivity for a hypothetical right-handed intermediate vector boson, expressed in terms of its mass, should reach the 800 GeV scale. This experiment, known as E614, has a two year construction phase, and is expected to take data in 1999.

Canada already has initiatives in several other low and intermediate energy projects that are expected to grow in size and coherence. Several groups are already involved in experiments at Jefferson Lab, where they have been collaborating on several Hall A experiments to precisely measure electromagnetic "form factors" of the proton as well as short-range nuclear effects. A collaboration of Canadian physicists has also joined the G0 collaboration in Hall C, which will measure parity violations due to the strange quark content of the nucleon. A smaller group of Canadians are also involved in the PHENIX experiment at RHIC.

These research efforts must be carefully planned so that sufficient focus is provided to maintain a coherent effort. In particular, the total number of such projects is expected to remain small but to grow in size as current research programmes at TRIUMF, SAL and other offshore facilities are completed.

3.3.5 Future Canadian Opportunities

We have identified a number of future subatomic physics experiments and studies that Canadian scientists could participate in, but are currently prevented from doing so by lack of capital or operating funds. We list a number of these to illustrate the possibilities that the GSC has available to it if additional funding were made available.[2]

- Construction of the ISAC facility appears to be ahead of schedule and low energy beams may be available as early as fall 1998. An earlier start to the nuclear physics programme accessible with the medium energy beam (1.5 MeV/nucleon) is particularly interesting and getting to this science as early as possible would allow Canada to rapidly assert its leadership at this frontier. This would require earlier funding for the necessary scientific instrumentation to carry out this programme.

- The ATLAS experiment has received capital funding for construction of parts of the liquid argon calorimeter systems and electronics readout systems. However, these contributions are insufficient to fund any one single subdetector system and leave the Canadian effort dependent on currently unidentified international resources. It also fails to utilise a significant fraction of the scientific and technical resources of the ATLAS/Canada group. Additional capital funding would significantly enhance both the Canadian technical and scientific contribution.

- The current funding plan provides sufficient capital and operating resources to allow SNO to meet its scientific goals. However, several additional cosmological and astrophysical experiments could be performed taking advantage of the very deep, low-background environment of the INCO mine and the infrastructure already funded and in place. Funding for the necessary instrumentation R&D and procurement is currently not available, although numerous Canadian proposals have been made.

These represent a selection of the future research opportunities that currently are not being pursued due to funding constraints. We believe that incremental increases in funding of even 5% per annum (or $860K) would allow several of these to be adequately funded. We also note that in order to match the necessary capital funding profiles for ISAC and ATLAS, operating support for the ongoing programme has had to be dramatically reduced to a level that is impairing Canada's ability to complete these experiments. We would expect that the GSC would use some fraction of any additional funds to help remedy this short-term problem.

3.4 Canadian Subatomic Physics Today

3.4.1 High Energy Physics

Standard Model Tests with OPAL

The large electron-positron (LEP) collider at CERN was built to serve as a factory for production of the Z^0 boson at low energies (LEP I: 100 GeV) and W^+ and W^- bosons at higher energies (LEP II: up to 190 GeV). Copious production of these bosons allows us to make precision measurements of their production and decay rates, a vital component of the unified gauge theory describing the electroweak interaction. This allows us to learn about the fundamental parameters in the electroweak theory such as the Weinberg angle and coupling constants. The higher energy collider,

[2] We note that almost all of these reflect proposals that have been made by Canadians to NSERC that, to date, have not received support. Although we are not in a position to properly peer review the proposals, the subcommittee considers the science inherent in each one to be compelling enough to deserve mention here.

LEP II, started operation in 1995 and is ideally suited for a study of the triple gauge couplings, precision measurement of the W boson mass and searches for Higgs particles with masses up to 95 GeV/c^2. Finally it may lead to the discovery of new phenomena such as supersymmetric particles or deviations from the Standard Model. Operation of LEP II is expected to continue until 2000.

OPAL is one of the largest efforts in Canadian subatomic physics and one of the most visible. The Canadian group represents about 20% of the OPAL collaboration, and includes researchers from CRPP, TRIUMF and the Universities of Alberta, British Columbia, Carleton, Montréal and Victoria. Canadians have achieved high visibility at CERN by concentrating their efforts at LEP on the OPAL experiment, and by focussing their physics analyses on a few well-defined areas of expertise.

Canada has been involved in the OPAL experiment from its outset in the early 1980's. Canadians supplied critical elements of the OPAL detector and data acquisition system, including a high precision vertex chamber, 4-m long Z-coordinate chambers, the pressure endcaps for the 4 bar central detector pressure bell, and a computerised system to reconstruct and monitor the data as they are collected. Canadians have also played a leading role in the development, construction and installation of the OPAL silicon microvertex detector and a set of tile scintillation counters for the endcap region.

Canadians have been leaders in several major analysis areas within OPAL, in addition to providing leadership in virtually all facets of this project. At various times, Canadians have been the overall physics co-ordinator, leader of the tau lepton (τ) physics group, leader of the Z^0 lineshape group, and leader of the lifetimes group. A Canadian is currently a member of the LEP electroweak working group and another is serving in the important LEP energy working group.

Canadians have built on their contributions to the OPAL tracking systems by focusing on those aspects of the data analysis where these devices are crucial. In so doing, they have become internationally recognised leaders in physics topics involving tau leptons, heavy flavour hadron lifetimes and QCD measurements. Figure 3 shows the OPAL measurements of the tau electronic branching ratio versus lifetime, and illustrates the precision of these measurements. A few examples of other areas of Canadian specialty are:

- precision electroweak measurements: τ lifetime and branching ratio, polarisation and forward-backward symmetry, leptonic neutral current couplings;
- QCD measurements: running of the strong coupling constant; fragmentation from exclusive hadron spectra;
- heavy flavour physics, including b-hadron lifetimes;
- searches for Higgs bosons, measurement of the Z° "invisible width" to look for new physics and other phenomena beyond the Standard Model.

At LEP II, the W boson mass has already been determined to a precision of approximately ± 200 MeV and additional data will make these measurements very competitive with the best data from the hadron colliders. Important contributions have been made by the Canadian group to the measurement of the W^+ mass at threshold and to the pioneering work on reconstructing the W^+ mass from jets. Canadians have concentrated their effort on excited lepton searches and on

Figure 3: The OPAL measurements of the electronic branching ratio of the tau plotted against the tau lifetime. The band is the prediction assuming $\mu - \tau$ universality and its width reflects the uncertainty associated with the tau mass.

studying events with photons and large missing energy, $e^+e^- \to \nu\bar{\nu}\gamma$. These studies provide both tests of the Standard Model and searches for excited neutrinos and SUSY particles.

The LEP II data are being collected in parallel with the ongoing physics analysis of the LEP I data. Five million hadronic Z^0 decays were recorded by OPAL during LEP I, and many analyses are now being finalised using this data set. Members of the Canadian group were primary or secondary authors on one third of the 180 papers already published by OPAL, representing an enormous intellectual contribution to the experiment. To date, 14 M.Sc. and 15 Ph.D. degrees have been awarded by Canadian universities for research carried out within OPAL and at present approximately 25 students are engaged in the OPAL research programme.

High Energy *ep* Scattering Measurements with ZEUS

The *ep* collider at Hamburg (HERA) is intended to provide us with information about the structure of a nucleon at very high momentum transfers (Q^2). Precision data will provide us with stringent tests of the Standard Model and the internal constituents of the nucleon. Such studies may lead us to new physics such as leptoquarks, supersymmetric particles, compositeness in quarks and leptons and right-handed weak currents. Discovery of any of these phenomena would be simply breathtaking, as they would point out what underlies the Standard Model. Indeed, if the recent observations [5] of an anomalously high e^+p cross section at very large momentum transfer by the ZEUS and the H1 collaborations are confirmed by more data in 1997, it will be dramatic evidence for new physics.

Canadian physicists have played a major role in the ZEUS experiment at HERA from its inception and design in the early 1980's. Canadian physicists have taken leadership roles in the ZEUS research effort: For example, a Canadian was deputy spokesperson of the experiment for several years and was responsible for the organisation of the overall physics research effort within the collaboration. Canadian physicists have been in the forefront of the physics analysis effort and two Canadians have been coordinators of physics sub-groups. Canadian physicists have also been involved in enhancements to the detector and have proposed, built and commisssioned a forward neutron calorimeter aimed at tagging pion exchange for pion structure function measurements.

The Canadian group, consisting of researchers from McGill and York Universities and the Universities of Toronto and Manitoba, took responsibility for the design of the forward and rear calorimeters, and fabricated half of the components in Canada. This device is state-of-the-art, being constructed from depleted uranium and scintillator plates that allow the calorimeter to measure particle energies to very high precision. The Canadian group was also responsible for the design, acquisition and implementation of the Third Level Trigger (TLT), a real-time, high performance computer system that filters the collisions before they are recorded by the detector. This system efficiently identifies real ep events from background interactions that would otherwise have to be rejected later in the physics analysis. As the HERA luminosity has increased, the system software has become much more sophisticated, and has been upgraded in order to select just the most interesting fraction of the ep cross section.

The initial ZEUS data have produced a number of results on a variety of physics topics. These include new measurements of the structure function of the proton now extended into the very interesting "low x" kinematic region (x represents the fraction of momentum of the proton carried by the quark or gluon), where the structure function is seen to rise dramatically. Other measurements include the observation of diffractive phenomena and "rapidity gap" events, studies of high energy photoproduction and the quark/gluon content of the photon, measurement of high Q^2 neutral and charged current cross sections and several searches for exotic particles. Many of the ZEUS papers have been the result of physics analyses with major contributions by Canadian researchers and their students, including, for example, the measurement of the F_2 structure function and energy flow in deep inelastic scattering, the measurement of the total γp cross section, the observation of colour singlet exchange between jets, the measurement of α_s, the observation of leading neutrons, and the search for leptoquarks.

The annual integrated luminosity at HERA has increased significantly each year, making new physics topics accessible. With the higher luminosity, the very high Q^2, deep inelastic scattering region will be explored. The full programme at HERA includes measurements with longitudinally polarised electron and positron beams that will extend until 2005, aiming for a total data sample of 1 fb^{-1}.

The ZEUS effort is expected to continue as one of the two major Canadian particle physics experiments well into the next decade. To date, 24 Canadian students have undertaken their Ph.D. research on ZEUS. Twelve have completed their studies, 11 with Ph.D. degrees and one with an M.Sc. degree, and 12 are currently performing M.Sc. or Ph.D. research.

Proton Spin Studies using HERMES

Quarks and gluons possess spin and the forces between them are spin dependent, leading to a rich variety of spin-dependent phenomena. In particular, it is a significant challenge for models of nucleon structure to describe the spin dependent quark distribution functions of the nucleon. Information about this spin dependence is being obtained by the HERMES experiment, which is measuring the asymmetry in deep inelastic scattering (DIS) of longitudinally polarised leptons from polarized nucleons.

The physics programme for HERMES is very broad and includes the determination of both the x dependence and the integral of the polarised structure functions $g_1(x)$ and $g_2(x)$ for both the proton and the neutron, as well as the crucial semi-inclusive measurements mentioned below. Experiments done to date have concentrated on inclusive scattering and have shown that at only a small fraction of the spin of the nucleon comes from the spin of the quarks. Progress in this field requires the determination of the contribution to the nucleon spin from the different components of the nucleon such as valence and sea quarks, gluons, and orbital angular momentum. These contributions can be isolated by detecting hadrons in coincidence with the scattered lepton. HERMES is the only experiment which will get decisive data on semi-inclusive processes because of the large acceptance of the spectrometer combined with hadron identification and the purity of the targets.

HERMES took data in 1995 with a polarised ^{3}He target and switched to hydrogen in 1996. The 1995 data have been analysed and preliminary results have been presented for $g_1^n(x)$, semi-inclusive processes, and results from unpolarised targets of hydrogen and deuterium. Final results for $g_1^n(x)$ have been accepted for publication in Physics Letters.

Canadians have a leading role in the experiment, taking on important management positions in the collaboration. For example, the Canadian group provided the deputy spokesman, who coordinated the design, installation, and commissioning of all components of the experiment; the tracking coordinator who participated in the detailed design of all tracking chambers; and several sub-system coordinators (gas systems, slow controls, electronics). Canadians were also a driving force behind the design and commissioning of the transverse beam polarimeter as well as tests to prove that the positron beam can be polarised.

The Canadian group provided the Transition Radiation Detector (TRD) including the sophisticated TRD gas system, and the Drift Chamber gas system. This large area device has yielded the best performance of any TRD in existence. Canadians also played an important role in the design of the upgraded beam polarimeter, the slow controls system, the readout electronics and the detector support system. They have also been instrumental in the development of the general software framework for data analysis as well as the algorithms for particle identification using all of the PID detectors in the spectrometer including the TRD.

The Canadian group has reduced its hardware responsibility to the TRD and associated gas system in order to concentrate its efforts on physics analysis. Canadians are making important contributions in the areas of inclusive scattering (g_1^n), semi-inclusive physics (ρ production, π asymmetries and charm production) and physics with unpolarised targets. The group is providing analysis coordinators for ρ meson production, unpolarised physics and particle identification.

Rare K Decays

The study of the decay of kaons has been a rewarding source of unexpected discoveries about the fundamental questions in particle physics. In particular, CP violation has so far been observed only in the neutral K system. However, CP violation is a necessary requirement for an asymmetry in the amount of matter and antimatter in the universe. Two weak decays of kaons, $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0_L \to \pi^0\nu\bar{\nu}$, are highly suppressed and can only be realised in the Standard Model as second order processes. The measurement of these branching fractions together would unambiguously confirm the Standard Model picture of CP violation. The E787 experiment has as its goal the first observation of the $K^+ \to \pi^+\nu\bar{\nu}$ decay. It is underway at Brookhaven National Laboratory, and is a collaboration between BNL, Princeton University, Japan and TRIUMF.

Canadian scientists have played leading roles in this experiment; for example a Canadian is a co-spokesperson. Scientists at TRIUMF and University of Alberta built a unique low mass drift chamber and instrumented the scintillating fibre active target with custom GaAs charge-coupled device transient digitizers. The Canadian group has provided a substantial part of the detector software, and the data are being analysed at TRIUMF. TRIUMF scientists collaborated with BNL on the construction of a special low-background beamline for E787.

To date, this experiment has improved the upper limit on the branching ratio of $K^+ \to \pi^+\nu\bar{\nu}$ by two orders of magnitude. Data is being analysed that will extend the sensitivity to 1.5×10^{-10}. New branching ratio values have been established for the decays $K+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\gamma\gamma$ and $K^+ \to \mu^+\nu\gamma$ as well as for other modes. Limits on particles like axions, hyperphotons, fermilons and other Goldstone bosons have also been established.

E787 will continue to take data for the next two years. Members of the Canadian group are participating in a proposal to perform the $K^0_L \to \pi^0\nu\bar{\nu}$ branching ratio measurement, which would see data taking start around the year 2000.

Heavy Quark Studies using CDF

The most fruitful ground for searches for new particles or interactions traditionally has been at the high energy frontier. Since 1986, the Fermilab Tevatron Collider has provided such a frontier, producing proton-antiproton collisions at a centre-of-mass energy of 1.8 TeV. The Canadian effort, although modest in size compared to the entire Collider Detector at Fermilab (CDF) collaboration, has made significant contributions to the project and has allowed Canadians to participate in this exciting research.

The results from CDF in recent years have been simply spectacular: the collaboration has discovered the top quark[4], it has made substantial improvements in measurements of the electroweak interaction, and is pursuing a strong program in b quark physics. The IPP group has been responsible for upgrades to the data acquisition system, and online and offline software development and management. Canadians have served as coordinators of the overall software development and data analysis effort, and the top and bottom quark physics groups. The physics research by this group has focussed on the top quark search and high-statistics studies of b-hadron production and decay. These studies have resulted in the largest sample of top quark decays and precise measurements of hadronic bottom meson decay branching fractions. The first Canadian Ph.D. student working on

CDF graduated in 1996, and three more are expected to complete their dissertations in the next year.

The group is proposing to participate in the current CDF upgrade program leading to a new higher luminosity phase of the experiment called Run II, which starts data collection in 1999. This next step will allow the group to make much improved measurements of the top quark properties and permit very high-statistics B physics studies. Most members of the Canadian CDF group are also involved in the ATLAS project and their proposed technical contributions and physics research are well matched to their expected ATLAS work. Thus, the Run II CDF effort will keep Canadian physicists at the high energy frontier and provide a smooth transition to work at even higher interaction energies.

3.4.2 The TRIUMF Physics Programme

TRIUMF is the heart of the subatomic physics programme in Canada. The in-house research programme is focussed around experiments that make use of the high intensity particle and polarised proton beams produced by the cyclotron. The physics programme at TRIUMF is diverse and includes studies of nuclei, fundamental experiments in particle physics and applied programmes in condensed matter physics and life sciences. The many diverse particle beams and precision nuclear techniques make the wide range programme possible. There is a large community of users ($\sim$ 700 in all) that carry out their research effort at TRIUMF.

TRIUMF embarked on its current five-year programme with three primary objectives: to maintain an active research programme using the existing facilities, to construct the ISAC radioactive beam facility, and to make the Canadian accelerator contributions to the LHC. TRIUMF also has as its mission the support of accelerator based research in Canada and the provision of technical infrastructure to the Canadian subatomic physics programme.

Strong Interaction Physics

At TRIUMF energies, one expects that quark degrees of freedom will start to play a significant role in the interpretation of many processes. Models have been developed that, while based on the mesonic picture, preserve the underlying symmetries of QCD. Predictions from these chiral perturbation theories have been made for observables that are accessible at TRIUMF energies.

Symmetries provide a window into quark degrees of freedom in hadrons. Chiral symmetry breaking reflects the u(up) and d (down) quark finite masses while charge symmetry (CS) breaking reflects the difference in mass of the two light quarks. This latter effect was first seen and studied at TRIUMF in np elastic scattering at beam energies of 487 and 347 MeV [7], using the world's best polarised proton source.

The other main theme of research in the strong interaction sector has to do with the understanding of nuclear properties and of the strong and weak forces in a multinucleon environment. For example, how does a nucleon in an excited state propogate through nuclear matter? How is the weak interaction of a proton modified when it is embedded in a nucleus? Does the induced pseudoscalar coupling constant g_p determined via the measurement of the radiative capture of a negative muon on the proton agree with nonperturbative QCD calculations?

Within the last four years two new large magnetic spectrometers, CHAOS and SASP, have been commissioned to address some of the above issues. They are characterised by large angular acceptance in the case of CHAOS and large momentum acceptance for SASP.

The physics programme of CHAOS includes:

- Systematic and precision studies of the elementary πp scattering amplitudes at energies below and around the Δ resonance via measurements of differential cross sections, asymmetries and cross sections in the Coulomb-nuclear interference region.

- Measurements of $(\pi, 2\pi)$ reaction. Preliminary values for the $\pi\pi$ scattering lengths have been obtained and compared with the predictions from chiral perturbation theories.

- The search for exotic multiquark states. CHAOS will survey the double charge exchange reactions with the objective of laying to rest or discovering the hypothetical dibaryon resonances.

The CHAOS programme in particular is receiving worldwide recognition for its impact in pion physics at intermediate energies.

The proton spectrometers SASP and MRS are being used for a new search for charge symmetry breaking effects in the inelastic reaction $np \to d\,\pi^0$ and searches for dibaryon resonances and deep lying pionic states. The charge symmetry breaking (CSB) experiment will complement the previous measurements by getting information on specific mesonic interactions.

Extensive studies have been carried out to study collective excitations in nuclei. Special provisions of a neutron beam helped to complement the experiments with the proton beam. These measurements provided an important look at the spin and isospin symmetries in nuclei and the corresponding nucleon-nucleon interaction.

Weak Interaction Studies

The decays of π mesons and μ leptons, rare decays and parity violation in atomic and hadronic systems have historically been used to provide unique information on the fundamental weak interaction structure and on couplings to mesons.

A TRIUMF measurement of the $\pi^+ \to e^+\nu_e$ decay rate has been pushed to the 0.4% precision level and shows that the leptons of the first and second generation have exactly the same weak interactions.

The weak interaction of quarks induces parity violation effects in hadronic reactions, though these effects are usually small and difficult to extract from the much stronger nuclear effects. An experiment is being conducted to measure a parity-violating asymmetry in proton-proton scattering, to a precision of 2 parts in 10^8. The data-taking phase of the parity violation experiment in pp elastic scattering is taking place over the next two years at two energies.

The radiative capture of muons has shed new light on the details of the weak interactions in a strongly interacting system. The results give information on the fundamental nature of the partial conservation of the axial current.

TISOL Physics

The TISOL test facility was built at TRIUMF several years ago to establish the feasibility of developing radioactive beams. Two unique ion sources have been developed (surface ionisation and electron cyclotron resonance sources) and now deliver high flux alkali metallic or volatile and noble gas ions. This has enabled the mounting of an active physics programme.

Several important measurements crucial to our understanding of the stellar evolution have been undertaken with spectacular results. The most publicised of these is the "Red Giant" measurement, where the rate of carbon burning via the process $^{12}\mathrm{C} + \alpha \rightarrow\ ^{16}\mathrm{O}$ was determined using a novel technique [6]. The result of this experiment, summarised as the astrophysical "S" factor for the process (a quantity proportional to the cross section for the process of interest), along with the data obtained at higher center of mass energies, is shown in Fig. 4. Prior constraints on this rate were uncertain by several orders of magnitude because of the difficulties associated with extrapolating measurements from higher energies. It is anticipated that the new ISAC facility will expand the studies to a larger class of experiments with astrophysics implications.

The new main activity at TISOL is the development of an ultra-high vacuum beamline and a clean room for trapping neutral radioactive atoms in a laser trap. This laser trap facility, known as TRINAT, has successfully demonstrated trapping of $^{37}\mathrm{K}$ and $^{38}\mathrm{K}$ isotopes, and the groups are now starting measurements of beta decay correlations. Preparation for trapping francium isotopes are underway in order to measure the atomic parity violation effects in these nuclei.

Atomic Physics with Muonic Hydrogen

An international collaboration is studying atomic cross sections for muonic hydrogen, muonic deuterium and muonic tritium scattering off hydrogen, deuterium and tritium in the electron-Volt energy region where one expects to find new resonances. Knowledge of these cross sections is important for the study of the muon-catalysed fusion processes and the understanding of few-body atomic systems. Measurements of the rate constants for $\mathrm{p}\mu\mathrm{p}$ and $\mathrm{d}\mu\mathrm{d}$ molecule formation in solids have been completed.

External Research at Low and Intermediate Energies

There are several research activities that involve TRIUMF and university-based researchers at other laboratories. At the KEK laboratory in Japan, Canadians are involved in a study of the energy levels of kaonic atoms. Hypernuclear decay of light nuclei and the K-nucleon interaction are being studied using the quasi-free reactions with kaons. A TRIUMF-KEK collaboration has initiated a programme, funded jointly by NSERC and Japan, to study CP violation observables in charged kaon decay. Canadians have played a part in searches for new hadronic particle states at BNL.

Canadian researchers are also involved in the FINUDA experiment at the DAPHNE laboratory in Italy (this is a ϕ factory that produces copious amounts of K mesons). Low-energy K-nucleon scattering measurements have been proposed as a way of testing chiral perturbation theory, and follow a programme of similar pion-nucleon scattering measurements at TRIUMF.

Figure 4: The observed S factor (a product of the cross section and other quantities) for C burning in the “Red Giant” experiment at TRIUMF. The TRIUMF data is at a centre of mass energy of 300 keV and the other data come from previous work. The fitted curve represents the predicted energy dependence when the TRIUMF data is included.

3.4.3 Nuclear Structure and Electromagnetic Interactions

Electromagnetic Interaction Studies

The new CW electron beams that recently became available worldwide are sophisticated and sensitive tools to probe strongly interacting nuclear systems. For the first time, final-state reaction products can be correlated with well-defined real or virtual photons. The higher energy facilities such as those at Jefferson Lab will explore the nuclear systems in the region where quark effects may play an important role. The Saskatchewan Accelerator Laboratory is well-suited for studies in the threshold pion production region, due to the 300 MeV maximum energy of its electron beam.

A tagging facility at SAL provides a photon beam for photonuclear reaction studies. The facility supports a variety of large detector systems including a large acceptance detector (SALAD) for reaction studies, a π^0 spectrometer (IGLOO), a neutron detector array, a large NaI detector and a newly commissioned spectrometer for electron scattering experiments.

The major physics accomplishments relate to tests of chiral perturbation theory, that is expected to provide a good understanding of the dynamics in the threshold region. The important results have been:

- polarisability of the nucleon and its modification in nuclear media,
- threshold photo-pion production on p and n,
- multiple nucleon emission in photon interactions with light nuclei, and
- electro-pion production at threshold.

Unfortunately this unique facility may have only a short life left. In April 1996, largely to find funds to support new initiatives, SAL was given a final NSERC grant for two years and was asked to look for alternate sources of funds. If funding for SAL is not found, Canadians using this facility will have to shift their research to laboratories outside the country or leave the country altogether to pursue their research programmes. The facility was used by numerous groups outside Canada, and the closing of SAL is a big disappointment to this international user community.

Experiments at Jefferson Lab have been the focus of attention for researchers at University of Regina. The team has played a major role in constructing and commissioning many of the detector systems for two high resolution spectrometers in Hall A. The group is playing an important role in numerous experiments that will explore the transition region from the mesonic and nucleonic degrees of freedom to quarks and gluons. It is anticipated that this will yield important information on short-range correlations, the onset of perturbative QCD, the strange quark content of the nucleon and precision meson and nucleon spectroscopy.

This same group has pioneered and led a research effort at the Institute for Nuclear Study in Tokyo, to address the critical issue of nuclear medium modifications of the rho meson. These studies test the predictions of chiral perturbation theory and non-perturbative QCD. The results of this experiment have attracted world-wide attention from theorists and experimentalists alike.

More recently, a group from University of Manitoba has joined the G0 collaboration that will measure the parity violating effects due to the strange quark content of the nucleon.

Heavy Ion and Nuclear Structure

The Tandem Accelerator Superconducting Cyclotron at Chalk River (TASCC) is based on a powerful combination of a 15 MV tandem accelerator and a superconducting cyclotron with a beam energy of up to 50 MeV/nucleon for light ions and 12 MeV/nucleon for heavy ions. The nuclear physics programme has extremely high visibility internationally with numerous outstanding achievements:

- precision measurements of superallowed β decays that place stringent limits on the Cabibbo-Kobayashi-Maskawa quark mixing matrix,
- precision mass measurements,

- studies of superdeformed nuclei (2:1 axis ratio),
- the discovery of one isotope with different deformed shapes,
- the phenomenon of identical deformed bands in neighbouring nuclei,
- the study of hyperdeformed nuclei (3:1 axis ratio), and
- exclusive measurements of projectile break-up determining time scales, energy dependence and their statistical basis.

The TASCC facility was actively involved in applied programmes of direct relevance to nuclear reactors and in testing the effect of cosmic rays on materials in space. The tandem has been used for accelerator mass spectrometry to determine the environmental impact of radioactive waste and various other sources of pollution.

The TASCC facility has been in strong demand, with researchers from universities within Canada and abroad competing for beam time. The impact of these outstanding visitors on the research effort was enormous. Understandably, this research community is very disappointed with the decision to close down the facility at the end of March 1997. It is anticipated that some of the researchers will leave the country and the rest will have to focus their immediate research programme abroad. Several of the most productive instruments are being temporarily relocated to facilities offshore, and plans exist for their return to continue their physics studies at ISAC.

Ultrarelativistic Heavy-Ion Physics

The primary motivation for producing heavy ion collisions at ultrarelativistic energies is the study of nuclear matter at extreme conditions of temperature and density where QCD predicts that nuclear matter must undergo a change of phase to a new state of matter, the quark-gluon plasma (QGP). Such an ambiance is conjectured to have prevailed in the very early universe. Ultra high-energy heavy-ion collisions offer the first opportunity for observing directly the parameters of the predicted phase transition, and to study the physical properties of the QCD vacuum state. The study of this new form of nuclear matter is the main motivation for the construction of the Relativistic Heavy Ion Collider (RHIC) at BNL. This collider will accelerate colliding beams up to centre-of-mass energies of 500 GeV for protons and 200 GeV/u for Au nuclei. These beams are expected to be available for experiments in 1999.

When completed, the LHC, though not a dedicated heavy ion collider, will provide beams with energies of up to 3.8 TeV/u for Pb-Pb collisions. At this energy, the asymptotic degrees of freedom will be much more stringently tested, and the QGP thus created will provide valuable insights into the parton distributions.

Canada has initiated a modest effort in this new frontier of subatomic physics. A team from McGill University has been involved in the PHENIX experiment at RHIC since its inception, and it has the primary responsibility for the construction of one of the PHENIX tracking subsystems. The detector should be ready for commissioning by the end of 1998.

3.5 Theoretical Subatomic Physics

The Standard Model provides the underlying basis for the interactions among quarks and gluons that constitute the fundamental constituents of all matter. The experiments at colliders have provided some of the most stringent tests of the model. The discovery of the top quark completes the three generations of quark doublets. At the next level the experiments will look for Higgs particles and for small deviations from the Standard Model. These deviations may arise from the discovery of supersymmetric partners of the particles discovered so far. Some of these are speculations that have to be tested and then established as reality within a general structure of a consistent theory.

It is to be emphasized that the success of the Standard model has lead to a unified view of subatomic physics. It has at the same time helped to establish links with astrophysics and cosmology. Canadian theoretical subatomic physicists have made important contributions towards an elucidation of the Standard Model and its applications at a phenomenological level. There are numerous outstanding contributions towards understanding the structure of the quantum field theory in general and the non-Abelian gauge field theories in particular (Semenoff, Kobes, Kunstatter and Leibbrandt). Methods to improve the perturbative treatments have been considered (Lam). Canadian theorists led the effort to develop the highly successful description of the structure of mesons and baryons using a non-relativistic Schrödinger approach in a QCD inspired potential (Isgur and Karl). Heavy quark effective theory was developed in Canada (Isgur and Wise) and numerous applications and refinements have been considered recently (Luke). These approaches provide us with a better understanding of the structure of baryons by giving a detailed description of the decay rates (O'Donnell and Kamal), which are crucial for extracting electroweak parameters of the Standard Model.

Canadians are taking a leading role in high energy physics phenomenology. They have made important suggestions for the measurement of fundamental parameters in the Standard Model, for precision tests of the model, and for searches for physics beyond the Standard Model (Godfrey, Kalyniuk and Burgess). This work has led to many experimental measurements and is important in the planning of future experiments. Canadian phenomenologists have played a crucial role in the interpretation of experimental results and in the comparison of these results with candidate theories. They continue to be at the forefront of the field in the interpretation of experimental measurements that could lead to contradictions with the current paradigm.

Important contributions have been made to find a non-perturbative explanation of baryon decays by solving the gauge theory on a lattice. The results have been very promising (Woloshyn and Trottier). The lattice gauge theories at finite temperature have provided a prediction for the critical temperature for the confinement-deconfinement transition that will be tested by RHIC experiments (Das Gupta and Gale). The quark-gluon plasma generated in this transition lasts for a brief period of time but provides a unique window on its properties. A study of the decay of plasmon modes and the problem of the gauge non-invariance of the gluon damping in QCD has been resolved due to efforts by physicists working with the thermal field theories. The Ward-Takahashi relations play an important part in this analysis (Takahashi).

In the study of the formal properties of quantum field theory, extension to finite temperatures has been highly fruitful. The development of Thermofield Dynamics has been largely initiated in Canada (Takahashi and Umezawa) and is now pursued in many other places. It is a development distinct from the usual Schwinger-Keldysh approach. First calculations of the effective potential of the Polyakov loop operator for four dimensional QCD was carried out by a Canadian (Weiss). The finite temperature field theory still provides an important venue for developments leading to non-equilibrium phenomena. The general techniques of quantum field theory, at both zero and finite temperatures, have yielded a wealth of interdisciplinary applications. Applications to many-body systems, nuclear systems as well as condensed matter systems, have been pursued vigorously over the years with outstanding results. And it is to be stressed that some of these ideas are being applied to topics such as astrophysics and cosmology.

Numerous extensions to the Standard Model, including Technicolor and Supersymmetry, have been undertaken with possible fermion mass generation in dynamical symmetry breaking and possible new physics (Holdom, London and Vishwanathan). One of the most popular extension of the Standard model is supersymmetry. A great deal of effort has been spent towards the formulation of a consistent supersymmetric theory and exploring the mathematical structure of such a theory (Meyer). At the same time an understanding of such a theory at a phenomenological level is being attempted through searches in collider experiments at CERN, HERA and FNAL. So far there is no indication of the presence of Supersymmetric partners to the well-known particles that are known. However this is still an avenue that will be followed with vigor in order to establish the presence of such particles or rule them out to a higher degree of certainty. These studies have implications for the Dark Matter that appear necessary to reconcile the most recent cosmological data that suggest a closed universe. Again, phenomenonlogical studies have been carried out to delineate clearly the implications of specific astrophysical, observations (Campbell). Contributions to such interdisciplinary studies have had a significant impact in the International community.

The nuclear many-body system has served as a useful laboratory to study the role of fundamental theories in a nuclear environment. One such important contribution has been the extraction of the matrix elements of the CKM matrix through a study of nuclear β-decay. Even though it would be interesting to learn about the role of quarks and gluons in the study of nuclear many-body system, it appears that the phenomenon in nuclei can be described better in an effective theory that replaces quarks and gluons by nucleons and mesons. One may construct a chiral perturbation theory that includes pions or add a phenomenology by introducing a set of mesons leading to a nucleon-nucleon interaction (Fearing). The problem is thus reduced to a problem of N-nucleons with two-body interactions. The role of mesons is excluded as a first approximation. However the origin of such an effective theory rests with the fundamental theory of strong interactions with appropriate electroweak interactions.

The role of mesons in nuclear structure and electroweak transitions may be ascertained by carrying out precision nuclear structure calculations. It appears that it will be difficult to attribute any particular effects to quarks and gluons directly. The only possibility is to carry out experiments at high energies with a large momentum transfer. Important Canadian contributions have been made to establish the role of mesons and isobars in the queching of Gamow-Teller transitions and in our understanding of the axial charge in nuclei (Towner and Khanna). It is interesting to note that these have required precision calculations in the usual many-body systems. These could be understood in terms of a field theoretic approach that requires the symmetry of the system to be preserved in any self-consistent approach.

The study of nuclear systems is more devoted to study the presence of various diverse phenomena that include the presence of collective states, fission of large nuclei and fusion of small nuclei. Each of these has made a large impact on our attempts to understand the details of nuclei. The finite nuclei may have surface vibrations in addition to the collective states. Add to these the presence of single particle states and we get a very rich spectrum of states and the associated properties of their decay provide us with a wealth of knowledge about the behaviour of a many-particle systems (Sprung and Wong). The study of collective properties of nuclei has been a focus of a great deal of research (Rowe).

The research program of the theoretical physicists is rich and diverse. There are numerous outstanding contributions to the formal aspects of the theory as well as its phenomenology. Important contributions have emerged from Canadian theoretical physicists with recognition in various circles world-wide. The fact that theoretical subatomic physics has prospered in Canada is particularly surprising given the near "starvation" levels of support that the community has recieved. Very often the support is barely sufficient to have a post-doctoral fellow or a student and not both. In recognition of this, the Fenton committee recommended that a significant fraction of any additional funding be allocated to support the theoretical subatomic physics effort. We concur with this conclusion as even a modest increase in research support will significantly enhance the availability of students and postdoctoral researchers, and allow more productive collaboration with colleagues at other institutions.

Recommendation 1 *The level of funding for theoretical subatomic physics recommended by the Fenton committee should be maintained (approximately 10% of the envelope, or $1.73M), and in a context where additional funding is made available, increased support of the theoretical programme should be considered.*

Despite this situation, the contacts between the theoretical and experimental programme has been vigorous and ongoing. Together, the two communities have effectively tackled many of the most important questions in subatomic physics. Continuing support of theoretical physics is essential to maintaining a healthy program in subatomic physics.

4 Dynamics of the Field and Training

The level of interest and excitement in a field can be determined by its recent evolution and by the quality of the training it provides. Subatomic physics still enjoys relatively strong growth and new young scientists are continuously appearing in the field. A survey of Canadian universities conducted by the subcommittee identified over thirty new hirings by Canadian universities of faculty or equivalent positions (IPP scientists) since 1990 and, at the time of this writing, three open positions are advertised. This does not take into account any hiring of subatomic physicists by national laboratories such as TRIUMF or TASCC. These young scientists are defining new directions and programmes in the field. It can be shown easily that these hirings are directly correlated to the new initiatives in subatomic physics and, conversely, that the new initiatives are partly a reflection of these hirings.

The dynamics of the field are also determined by the number of our graduates that find employment in teaching positions. In our survey, of the 85 recent graduates whose permanent employment status is known, one finds that roughly 25% have found academic positions in Canada or abroad, a reasonable rate of renewal within academia. A large number of the new university hirings mentioned above are researchers who either received their undergraduate or graduate degrees at Canadian universities. The remaining graduates are employed in primarily industrial positions where their problem-solving skills and technical background are sought-after assets. This is an excellent testimony to the success of the academic programme in Canadian subatomic physics.

The intellectual vitality of the field is demonstrated by the fact that through the years one has observed some important reorientation of the research programmes in subatomic physics at many universities. For example, the Laboratoire de Physique Nucléaire of the Université de Montréal, which was mainly dedicated to nuclear structure studies in the seventies, has largely reoriented its programme towards particle physics and is now one of the Canadian leaders in the OPAL collaboration at CERN. Similarly, the nuclear physics group at Queen's University has largely initiated the SNO project and this now represents the main activity in subatomic physics at that university. As a final example, we note the rapid increase in the size of the intermediate energy group at the University of Regina. Presently, many subatomic physicists at TRIUMF are in the process of reorienting their research programme from intermediate energy physics to the physics of radioactive beams at the ISAC facility now under construction. The renewal of the research programme is very much a continuous process.

Subatomic physics research provides an excellent training ground for young scientists. An education in physics gives students a unique ability in problem solving coupled to independent and critical thinking that prepares them well for either industry or academia. Their training encourages them to rely on basic principles and be rigourous in their analysis and research. Students in subatomic physics are, in addition, used to working with highly complex systems characteristic of many modern industrial situations. Furthermore, most of the students in the field are part of large teams and are trained to work in competitive atmospheres. Participation in these international collaborations, where they are exposed to some of the most creative and productive researchers on a global scale, prepares them to compete effectively in the present world economy. As discussed in Section 6, we can find numerous examples of contributions from subatomic physics to applied and interdisciplinary research and to the development of new technologies that are now used in industry. These successes are based on the unique expertise of subatomic physicists in radiation detectors,

Year	Physics Ph.D.	Experimental SAP	Theoretical SAP
1990	106	12	12
1991	131	14	9
1992	101	7	12
1993	128	10	13
1994	121	17	9
1995	150	14	11
1996	136	15	13
Total	873	89	79

Table 1: The number of Ph.D. graduates from Canadian Universities in physics, experimental subatomic physics and theoretical subatomic physics.

accelerator technology and accelerator based research, and on instrumentation in general.

Our survey results show that many graduates in subatomic physics find employment in the computer industry as system managers, programmers and other computer professionals, based on the expertise developed in their research work (computer modeling experience has been specifically highlighted). These skills are also the basis on which many graduates have found employment in the finance and banking industry, a domain not immediately viewed as related to subatomic physics. It is clear from our survey that the field currently provides excellent training with good employment opportunities. The vast majority of graduates in subatomic physics are finding positions that are well related to their training and interests.

The relative number of Ph.D. degrees granted in Canada in subatomic physics compares well with other physics disciplines. Table 1 lists the number of Ph.D. graduates in physics overall and in experimental and theoretical subatomic physics from 1990 through 1996. These data were obtained from the annual survey done by the CAP of physics Ph.D. degrees awarded by Canadian universities. During those years one observed a statistically significant increase in the number of degrees in subatomic physics. This increase tracks the increase observed in the total number of physics Ph.D. degrees awarded, with the fraction of subatomic Ph.D. degrees remaining constant at about 19%. This demonstrates that subatomic physics has maintained its attractive power for students interested in a scientific career.

5 Funding, Personnel and Infrastructure

5.1 Funding

5.1.1 Description of Funding Mechanisms

University faculty and TRIUMF scientists rely almost wholly on NSERC for their research funding. This includes the support of graduate students, postdoctoral fellows and other scientific personnel as well as equipment, including major installations. Generally most of the infrastructure support, such as salaries for engineers, technicians and programmers, is also funded by NSERC grants.

Subatomic physics is one of 26 disciplines or "selection committees" supported by NSERC. The allocation of resources for subatomic physics is handled differently from most of the other disciplines. The large projects and time scales typical of particle and nuclear physics experiments and facilities are best served by "project" grants that allow several people to collaborate on a multiyear project. Thus the majority of subatomic physics funds are allocated in this form. In addition, in order to facilitate planning, a fixed "envelope" of money is prescribed for subatomic physics (in other disciplines, large capital and equipment funds come from separate budgets). The amount in the envelope was originally set in 1991 on a historical funding average of approximately \$20M. The field is required to operate and provide capital for almost the entire programme inside this envelope (TRIUMF is a source of some equipment funds for specific projects such as ISAC).

Various types of grants may be applied for and awarded from the fixed envelope. These include the project grants previously mentioned; equipment grants and major installation grants (MIGs) to provide capital for experiments; and major facility access (MFAs) grants meant to provide the infrastructure required to use a large collaborative facility. The project, equipment grants and MIGs have generally served the community well. The MFA grants are only two years old and so it is difficult to evaluate their effectiveness.

5.1.2 Funding Shortcomings

The historical level of funding for subatomic physics has varied significantly over the last 15 years, as shown in Fig. 5. Recently the size of the envelope has been \$17.3M. The reduction in funds is partly due to an overall budget cut to NSERC as a result of the national budget cutting exercises of the Canadian government and partly the result of the first NSERC reallocation exercise. The Fenton Committee, as discussed earlier, produced a long range plan to deal with the reduced funding. The effects of the reduction in funding over the last two years is discussed in Section 7.1.

While the envelope gives very predictable funding, it lacks any mechanism to adjust to changes in the type of funding required in different years. For example, when there is little demand for equipment, operating grants can grow. When new experiments require capital to build equipment, the operating grants must be reduced, eliminating support for graduate students and postdocs working on ongoing projects.

As indicated earlier in this report, the field has been very successful in attracting new faculty members. These people have often joined the new initiatives such as ATLAS and BaBar. A completely rigid envelope funding mechanism lacks any way to fund new applicants and capitalize on new scientific opportunities, except by reallocating resources from existing projects.

Figure 5: Total NSERC funding for subatomic physics between 1980 and 1996. The components identified as operating and capital are shown separately. These figures have not been corrected for inflation.

In 1996, NSERC allowed some "forward borrowing" (allowing the use of grant funds from future year budgets in the current fiscal year) to fund a very modest contribution to BaBar and to provide the final three years of funding for SAL over two fiscal years. This is one mechanism by which the envelope can be made more flexible. Clearly, borrowing against the future is something that must be controlled very carefully or the ability to respond to new opportunities could be even more drastically reduced. However, it does provide the required flexibility to accommodate the rather large capital outlays necessary for new facilities and it appears to be a reasonable solution to the past inflexibility of the envelope.

In the 1997 grants competition, NSERC approved a longer-term "forward-borrowing" plan in order to accomodate the capital requirements of the ATLAS and ISAC experiments [8].

Recommendation 2 *NSERC should allow the GSC to "forward borrow" funds to accommodate variations in capital funding requirements of the programme. A specific policy should be adopted to enable the GSC to understand the constraints this presents and to ensure that NSERC staff can manage such forward-borrowing.*

5.1.3 Effects of $\pm 15\%$ Variations in Funding

The Fenton committee explored the opportunities presented to the field if NSERC provided 15% additional support to subatomic physics. Its conclusion was that the scientific opportunities provided by the ATLAS experiment was of such importance that approximately 40% of the additional resources would be directed to this project. The balance of the additional resources would be provided to fund new initiatives, improve support of the theoretical programme and to allow the ongoing projects and facilities (SAL and OPAL in particular) to complete more effectively their current research programmes.

Recommendation 3 *In a scenario where up to 15% of additional funding is made available to the subatomic physics GSC, funding should be provided to one or more of the new initiatives that have been proposed by the community. Potential projects are the advance of the ISAC physics programme, enhancement of the scope of the Canadian involvement in ATLAS, and the use of the SNO facility for Dark Matter or supernovae searches.*

The committee also examined the effects of a 15% reduction in funding. Their recommendation was that Canada would not be able to proceed with participation in the ATLAS experiment, and that support for the particle physics programme would have to reduced by almost 50% by the year 2000. Support for SAL would be discontinued in all scenarios, while support for the other on-shore facilities such as SNO and ISAC would be retained. Canada's contributions to subatomic physics would be severely handicapped and Canadian researchers would not be able to play a significant role at the high energy frontier.

5.2 Research Personnel

In the previous section the funding of university faculty, graduate students and postdoctoral fellows was mentioned. This aspect of research personnel was also covered in Section 4. There are three other categories of researcher in Canadian subatomic physics that play an essential role. These are the research scientists of TRIUMF, the Institute of Particle Physics and the Centre for Research in Particle Physics. The scientists working for these institutions form a core of research professionals that support the whole subatomic physics programme. It should be noted that their funding mainly comes from the NSERC envelope.

TRIUMF employs 40 experimental and 4 theoretical research scientists in continuing positions who are eligible to receive NSERC funding. In addition to their participation in the TRIUMF accelerator based research programme, they also provide a valuable liaison with outside TRIUMF users. TRIUMF scientists are also playing leading roles in non-TRIUMF accelerator experiments, including ATLAS, E787, HERMES and OPAL.

The Institute of Particle Physics is completely supported from NSERC funds. The IPP employs seven research scientists in continuing positions. Each scientist chooses a member university at which to reside, and presently there are scientists at Carleton University, McGill University, University of Toronto, University of British Columbia and University of Victoria. There is a very close working relationship between the university faculty and the IPP scientists. Over the last ten years, five IPP scientists have taken faculty positions in Canada and the USA. The research scientists work on the particle physics programme including ATLAS, BaBar, OPAL and ZEUS.

The CRPP is made up of the particle physics group originally attached to the NRC. This is now a separate institute located at Carleton University and employs seven research scientists. They are playing leading roles on OPAL, SNO and ATLAS, and provide occasional technical support to the rest of the Canadian particle physics programme.

A professional cadre of scientists is an essential requirement to participate in international projects where scientists from the other countries are generally supported by large national laboratories. The research scientists at TRIUMF, IPP and CRPP play that role in Canada. They have an international reputation for excellence, as evidenced by the high profile most of these scientists have.

Recommendation 4 *The number of research scientists supported by NSERC be maintained at the current level, and in the context of additional funding the number of research scientists should be increased.*

5.3 Infrastructure

Canadian subatomic physics research is supported by scientific and technical infrastructure that is essential to the health of the programme. TRIUMF is emerging as the primary centre for infrastructure support, providing engineering and technical assistance for both TRIUMF-based experiments and other subatomic physics projects.

TRIUMF is presently building the ISAC facility. This will be an important centre for particle and nuclear astrophysics into the next decade. It is also making an in-kind contribution of $30M to the LHC accelerator. These two activities, along with the in-house experimental programme, receive the majority of TRIUMF infrastructure support.

TRIUMF was involved in the construction of various subdetectors and electronics systems for the HERMES and E787 experiments. It has recently provided technical assistance to the SNO construction project, the BaBar central drift chamber construction and the ATLAS liquid argon hadronic endcap and forward calorimeters. TRIUMF also supports a small number of research positions (both faculty and research scientists) based at Canadian universities. These researchers play a key role in projects that involve their local university groups.

Recommendation 5 *TRIUMF's role as an infrastructure centre for Canadian subatomic physics research should continue to be supported.*

The Centre for Research in Particle Physics also plays an important infrastructure role, providing technical and research support to several of the particle physics projects and to SNO. CRPP (and originally as NRC) played a key role in getting the OPAL and SNO experiments started. The group has produced many of the gas detectors built by Canada for particle physics experiments, including a TPC, vertex chambers for ARGUS and OPAL and z-chambers for OPAL.

The university groups also receive additional infrastructure support from NSERC through the Major Facilities Access Grant programme, which funds engineers and technicians who typically contribute to several projects at any one time. The IPP scientists discussed in the previous section also provide a very important component of research support to the high energy physics programme.

Both the MFA and IPP programmes are considered essential to the future health of Canadian university-based subatomic physics.

The subatomic physics community is provided with computer network support through an NSERC project grant. This is administered centrally by a group of researchers and computer professionals based at Carleton and CRPP, which works to improve the computational infrastructure (network bandwidth, distributed file systems and video-conferencing) between Canadian institutions and between Canada and the foreign laboratories where Canadian subatomic physicists conduct research. There is no central computing facility for Canadian subatomic physics–each university group has developed local workstation clusters that are funded by NSERC equipment grants. This model meets the existing needs.

Two agencies, AECL and NRC, have both withdrawn from supporting subatomic physics research. This has particularly affected SNO which was relying on these agencies for infrastructure support. TRIUMF and CRPP have provided additional assistance to but do not have the financial resources to make up the entire loss. Predictable infrastructure is an essential requirement for the continued success of the subatomic physics programme.

Recommendation 6 *The NSERC GSC should maintain the support of subatomic physics infrastructure and the technical and engineering personnel funded by Major Facilities Access grants. Continued support should also be provided to computer networks used by subatomic physics through the HEPNET project.*

6 Applications, Interdisciplinary Research and Risk Taking

6.1 Applications and Spin-Offs

The latter half of the twentieth century has seen a dramatic increase in the application of technology. There can be no argument that a significant fraction of the global economy is driven by research and innovation. For instance, the areas of integrated semiconductor electronics, computers, polymers, materials technology, lasers, opto-electronics, robotics and process control have dramatically altered the economy and the way in which people live.

Our understanding of subatomic physics has also grown dramatically during the twentieth century. Numerous technologies have developed as a direct result of this growth in knowledge. The obvious ones include the nuclear power industry, nuclear medicine (both diagnostic and therapeutic), nuclear weapons and direct applications of radioactive sources (for instance, sterilisation of food, emergency lighting and long-lived, compact power sources). Less obvious, but probably of even greater impact, are the ways in which subatomic physics has affected almost all high technology endeavours.

The development of high resolution solid state γ and x-ray detectors has allowed quantitatively precise, very sensitive and non-destructive identification of the atoms that emit radiations. This technique is extensively used with radioactive tracers in biological and chemical systems to measure reaction rates, effects of trace chemicals and migration patterns. High resolution detectors are often coupled with various accelerators (also a subatomic physics innovation) to analyze non-destructively many systems. The oil-well logging industry uses neutron generators or neutron sources to analyze chemically the rock surrounding an oil well. X-ray fluorescence, PIXE (proton induced x-ray emission), PIGE (proton induced γ emission), Rutherford back scattering, neutron activation analysis, and neutron scattering are now widely used techniques to analyze devices, novel materials and conventional chemistry and biology assays. They are finding new uses in environmental studies in the search for trace chemicals or hazardous materials. Ion implantation uses accelerators developed for subatomic physics. Neutrons from reactors are used directly to dope semiconductors for specialised applications where dopant uniformity is critical (neutron transmuted germanium devices, for example). High energy accelerators are used to generate synchrotron light, which in turn is used for various types of materials analysis, x-ray and ultraviolet spectroscopy. As the microelectronics industry continues to decrease feature sizes in semiconductor devices, higher energy accelerators may find a role in the lithography process itself. Process control sensors (and home smoke alarms) often use radioactive sources and various types of detectors to measure density, thickness, or chemical composition.

Nuclear medicine uses a host of techniques, accelerators, and detectors that have been developed for subatomic physics research. Many of the newest methods of imaging – computerised axial tomography (CAT), magnetic resonance imaging (MRI), and positron emission tomography (PET) – all are based on developments in subatomic physics. Various analytic and diagnostic techniques make use of radioactive tracers (for instance, radioimmunoassay). Radiation is used directly as therapy.

Subatomic physics has also spawned several new technologies as a by-product of meeting particle detector or data analysis requirements. The World Wide Web was developed at CERN for high energy physics purposes. Faster, more dense and more precise electronics for data acquisition – multichannel analyzers, analog-to-digital converters, transient digitizers, and time-to-digital converters – have been developed as particle detectors required them. Real time computing and data acquisition, photomultiplier tubes, large, high-field superconducting magnets, conventional magnets and avalanche photodiodes are a few examples of areas that have been influenced by developments in subatomic physics.

Finally, one should mention that in any advanced technology, the most important developments are ideas and a basic understanding of the fundamental processes involved. These ideas (and people who know these ideas) can often contribute significantly in other fields. This has happened extensively between various subfields of physics and there are several leading theorists who have done important work, using related ideas, in both condensed matter and subatomic physics. Industry has realised that these ideas can be directly applied in their areas as well. Military organizations and "think tanks" employ physicists, not only for their technical expertise, but also to apply their modeling and quantitative analysis techniques to other types of problems. Theorists are employed by oil companies to apply path integral techniques, developed for fundamental particle physics calculations, to the problem of seismology. Banks and brokerage firms are employing physicists both to develop quantitative market models and to make "real time trading" systems.

Canadian contributions have been and continue to be significant.

The CANDU reactor programme is a completely Canadian R&D effort and product. The germanium detector, which is the basis for many of the analytic techniques that have been discussed, was invented at Chalk River Nuclear Laboratories. Neutron scattering, for which Prof. Brockhouse of McMaster University received the Nobel Prize in Physics, was developed at CRL. TRIUMF, in conjunction with Nordion and Squib, developed and is producing the vast majority of $^{92}Sr/^{92}Rb$ generators used in coronary diagnosis throughout the world. Approximately 60% of ^{60}Co sources used in food irradiation and in treatment of tumors are produced in Canada by CRL. The Nordion involvement at TRIUMF is particularly interesting (see box on next page).

An abbreviated list of various ongoing application projects, including corporate collaborators, in which subatomic physics research is playing a key role includes:

1. The ISOTRACE Laboratory at the University of Toronto, which uses Accelerator Mass Spectroscopy (AMS) for trace analysis and dating for research, archeology, and commercial purposes.

2. AMS using ^{14}C, ^{36}Cl and ^{129}I has been a large component of the applied programme at TASCC, supporting for example the High Level Waste Management Programme, Hydrology research and environmental safeguards monitoring (TASCC/AECB/IAEA).

3. Contraband detection, using resonant gamma ray absorption, accelerator technology and a photon imaging technique to search luggage for explosives and drugs (TRIUMF/Northrop-Grumman).

4. Avalanche photodiode improvements (EG&G, McGill University).

5. Computing/neural networks (Dendronic Decisions Ltd., University of Alberta).

6. Use of GaAs charge-coupled devices (CCD's) for development of circuits such as the 500 MHz transient digitizers employed in the E787 experiment (Micronet Center of Excellence, TRIUMF, University of Victoria, University of British Columbia).

NORDION and TRIUMF

Nordion International exploits two high intensity proton cyclotrons at the TRIUMF site for the production and delivery of radioisotopes mainly to the international medical community. TRIUMF operates the cyclotrons for Nordion and provides technical expertise on a cost recovery basis. Nordion is using technologies developed at TRIUMF under a licensing agreement. This includes isotope production methods, target and cyclotron technologies. Currently Nordion produces ^{123}I used in brain, heart and thyroid imaging , ^{82}Sr/Rb generators used in heart imaging, ^{67}Ga for soft tumour and abscess detection, ^{201}Ta for cardiac imaging and ^{111}In to detect inflammation and infection. TRIUMF obtains royalties as a percentage of gross sales. For the last few years Nordion has sold more than $10M of radio-pharmaceuticals from the TRIUMF site. The accelerator-produced isotopes complement the reactor-produced ones from CRL. More sales are expected as a result of the recent approval by the US Food and Drug Administration of a new iodine pharmaceutical based on fatty acids. UBC/TRIUMF also obtain 10 hours of isotope production on one of the Nordion cyclotrons annually. This is used to provide UBC researchers with specialty isotopes like ^{13}N and ^{15}O. The recent publication in *Nature* of a study of the growth potential for reforested clear cut areas was based on the study of nitrogen intake using radioactive ^{13}N . Similar studies for the World Rice Institute are being undertaken by researchers from UBC and could have a dramatic impact on rice production in the Asian countries.

7. Positron Emission Tomography (PET) Scanner (CTI/Siemens/TRIUMF, University of British Columbia).
8. Medical isotope production (Nordion/TRIUMF/CRL).
9. Proton therapy (TRIUMF/B.C. Cancer Agency, UBC Dept of Opthalmology).
10. Radiation damage studies for reactor materials and single-event upset in electronics (TASCC/ DREO/CSA).
11. Medical cyclotrons for the medical isotope market (EBCO/TRIUMF).
12. Drying of hay in the Peace River area using radio-frequency ovens (TRIUMF/ Northern Forage).
13. Commercial development of phototube bases and electronics (University of Regina/Saskatchewan Research Council).
14. Cryogenic scrubbing of smoke stack exhaust (TRIUMF/CDS Research).
15. The application of high-speed subatomic physics data acquisition techniques and programmes for factory control (Trent University, Peterborough Paper Converters, Inc.).

16. Application of microstrip gas chambers for x-ray detectors for wood processing (Tantalus Inc., TRIUMF) and for mammograms and dentistry (CRPP).

6.2 Applied Research Funding

In all the areas listed in the previous subsection, there are no obvious candidates for initiatives inspired by specific funding programmes. Many applications have developed naturally from a strong base of fundamental research and from personal contacts. Communication of research activities between disciplines and with industry is key to forging such contacts. NSERC and CAP could provide the forum for such contacts.

On the other hand, there should be no barriers to applied research with two caveats:

1. There are many cases where applied research is more appropriately funded by private investment.

2. Applied research that is supported by public funds should meet the same criteria of excellence as applied to basic research.

Many members of the subatomic physics community have felt that in recent years applied research has been promoted to a degree that seemed to undermine the balance and relationship between applied and basic research. Basic "curiosity driven" research is a long-term investment in the creation of knowledge. It does have a large economic impact through opening up new areas of applied research, which usually builds upon the successes and the ideas of basic research. Appropriate encouragement to transfer ideas into the applied research areas should be available, but not at the expense of basic research funding. Rather, such transfer should be considered as an add-on investment that will ultimately benefit both applied and basic research.

We note that many of the applications that have arisen from subatomic physics research have been facilitated by technology transfer programmes based at national labs. Universities should be encouraged to provide similar programmes. NSERC could play a lead role in coordinating and supporting these activities.

Recommendation 7 *NSERC should promote University-based technology transfer programmes, drawing on the experience gained at national laboratories.*

6.3 Interdisciplinary Research

There are several areas of study that do not fall into the category of conventional subatomic physics research but which have developed with the active participation of subatomic physicists. Interdisciplinary collaborations require techniques and apparatus that have been developed in one field of physics to answer questions that arise in another field. Most of the interdisciplinary cross-fertilization is happening through the demands of the discipline and/or through individual contacts.

There are several specific instances of interdisciplinary research that have worked well. As an example, the Canadian Microelectronics Corporation, an NSERC-funded organisation, has been very effective in collaborating with subatomic physics in several electronics developments efforts: The CDF, ATLAS and SNO projects have worked with this organisation to develop very large-scale integrated circuits for their readout systems. Facilities such as TRIUMF and CRL tend to foster multidisciplinary research. Neutron scattering facilities and techniques developed at CRL are used for materials analysis in condensed matter research and industry. The TRIUMF muon spin resonance programme, which exploits a property of parity violation in the weak decay of the muon, is a well recognised tool with significant impact in specific areas of condensed matter research (for example, vortices in superconductors and quantum diffusion of hydrogen-like impurities in semiconductors) and in chemistry (for example, radiolysis, radical formation and exchange reaction rates). Other interdisciplinary efforts make use of radioisotopes and radiotracers for research in botany, medical imaging, neurodegenerative disease diagnostics, and psychiatric research. Positron Emission Tomography is now a powerful tool in medicine–it relies on isotope production, imaging software and detector development, which are the common trade of subatomic physics, as well as radiopharmaceutical research and development. An international collaboration (including major electronics manufacturers and a Canadian subatomic theorist from McMaster University) is studying "quantum wires" and "quantum dots" in an attempt to find the limitations or new effects that come into play when components are reduced to such dimensions that quantum effects are non-negligible. Subatomic physicists from the Université de Montréal and Sherbrooke are working with the Defense Research Establishment Ottawa and the Space Agency on single event upset testing and radiation resistance of electronic components using beams at TASCC and TRIUMF.

The new ISAC facility at TRIUMF will have facilities dedicated to the condensed matter community (polarized ^{8}Li beams for the study of interfaces and thin films, and nuclear orientation apparatus for β-NMR studies). It will also provide the opportunity to produce and select new isotopes for research in nuclear medicine.

Research involving collaboration between disciplines should not face financial or administrative barriers. Since the quality of the researcher plays a key role in the evaluation of a research proposal and the value of the science may be judged by people in another discipline, a natural barrier for such efforts is always present. The only universally accepted criterion for funding is research excellence as judged by competent peer review.

Recommendation 8 *NSERC should continue to ensure that research grant applications that fall within the jurisdiction of two or more grant selection committees be adequately peer reviewed and that potential disincentives (such as transfer of grant funds from one committee to the next) not prejudice the review of such grant applications.*

Lessons can be learned from the way the TRIUMF μSR research programme has been funded. While the techniques of μSR were being developed, the main funding came from subatomic physics where the necessary expertise and techniques resided. Once established, the science done with μSR was more appropriately judged by the communities who were affected by their results (chemistry and condensed matter physics). This process worked because the bulk of the infrastructure needed for such research is supported by TRIUMF (outside the NSERC portfolio) while NSERC supports the teams who use the facility. This is a clear example of an appropriate use of a Major Facilities Access grant and the fostering of interdisciplinary research.

6.4 Risk Taking

The results of our survey indicated that the only universally acceptable criterion for funding subatomic physics is research excellence. The one caveat to the "excellence" criterion is that it tends to encourage conservative projects where one can document a reasonable certainty of success. There is some sentiment that this precludes some initiatives, particularly in areas such as instrumentation and technical developments, which cannot be shown to succeed before a significant research effort has been expended.

No specific recommendations have been made to counter this effect, except, perhaps to continue to emphasize to the grant selection committee the need to promote innovative research and to accept some risks in evaluating research proposals.

6.5 Public Outreach and Education

Efforts to communicate the results of subatomic physics research to the public are fragmented and uneven across the discipline. There are many scientists who are excellent communicators and who do participate in public outreach and educational efforts (through public lecture programmes, interactions with news media and through university public affairs departments). The community also makes good use of the World Wide Web to provide publicly available information on many of the research efforts. However, the subcommittee felt that public outreach and education could be significantly enhanced with a more coherent approach. A coordinated public outreach programme for Canadian subatomic physics would be a significant asset, but require coordination and a broad-based effort.

Recommendation 9 *The subatomic physics community should develop a coherent public outreach and education programme, building on the existing efforts at TRIUMF and other institutions. NSERC and CAP could play a coordinating role in this effort.*

7 Research Policy and Funding Issues

In our discussions with community members, a number of topics were raised that relate to the perceived strengths and weaknesses of the Canadian subatomic physics programme. We should note that in many cases, these are not issues specific to subatomic physics per se, but in fact are peculiar to the Canadian funding or political climate. We therefore note that solutions to some of the perceived weaknesses (and even the source of some strengths) are to be found outside the field.

7.1 Excellence of Research Personnel

The greatest strength of the Canadian subatomic physics research effort is the excellence of the individual researchers. Although often this is not properly appreciated, Canadian subatomic physicists have managed to make world-class contributions to advances in this field with limited facilities and resources. Canadian universities with subatomic physics groups have consistently made excellent hiring decisions, which is reflected in the faculty renewal currently taking place within these groups.

7.2 Selectivity and Availability of Funding

In a field so diverse both in terms of scientific questions and types of research collaborations, the subatomic physics community has been sensitive to the risk of attempting a large number of projects, thereby diffusing Canada's efforts in this field. This has clearly not happened: Canada has been able to play lead roles in large collaborations and yet support excellent national research programmes. Most members of the community feel that the NSERC subatomic physics GSC has demonstrated sufficient selectivity to strike the appropriate balance between large and small research efforts.

Of course, in such a complex and evolving situation, it is difficult to create a programme that has no weaknesses. The principal concern raised in this review has been the sheer lack of funding to adequately support all of the excellent research. This has meant that the GSC has had to apply a unreasonable degree of selectivity, refusing to support some new initiatives put forward in recent years and to reduce dramatically funding to excellent ongoing projects. An example of this is the decision to close the Saskatchewan Accelerator Laboratory. This has also meant that certain projects have been funded at levels that require the researchers to reduce significantly the scope of their work. The Fenton Report identified this clearly:

> "Due to the very limited resources available, the Committee reluctantly concluded that it will be necessary to phase out or reduce the scope of many promising research activities even before their originally targeted goals have been met. This is far from optimal, but it represents the best compromise we could make between the funding of ongoing and new projects to maintain a healthy balance in the discipline."

The effects of this compromise are now evident in the results of the last two NSERC funding competitions. Overall operating funding declined by close to 10% between 1995 and 1996, even though the SNO and ATLAS projects received significant increases in support. This has left some of the most important components of the ongoing programme virtually starved of resources. For example, funding for OPAL and ZEUS was reduced by 20% in one year, requiring both collaborations to significantly reduce their scientific staff. Yet both collaborations are in exciting stages of their scientific effort, taking data at either higher energies or higher luminosities. Other components of the programme received similar treatment. With expected increases in capital funding, the subcommittee is very concerned that further drastic reductions in operating support are inevitable and may endanger the viability of some of the projects.

The situation has been aggravated further by unexpected capital funding requirements for SNO detector construction. Since 1995, approximately $1.9M has been diverted from the subatomic physics envelope to fund capital cost overruns of this project. These unexpected capital costs have made it even more difficult to maximise the scientific potential of the existing programme.

A final consequence of these reductions in funding have been the inability of the subatomic physics GSC to set aside any funds for new initiatives in the next three to four years aside from the three highest priority projects. This is despite the recognition of the GSC that this will lead to an intolerable situation over the next several years as researchers complete the current experiments. Our estimate of the demographics of the field indicates that additional funding at the level of approximately 10% of the total budget is required to support new initiatives that are not part of the current scope of the three future projects.

Recommendation 10 *The NSERC GSC should allocate approximately 5-10% of the envelope to new initiatives, beyond what is currently outlined in the GSC Five Year Spending Plan. This should be phased in as rapidly as possible, but consistent with the longer term financial constraints faced by the GSC.*

The survey results and discussions with members in the community reflected frustration within the community arising from these issues.

7.3 The Balance Between Concentration and Diversity

Subatomic physics is a diverse scientific field that ranges from questions related to the structure and interaction of nuclei to very high-energy scattering of fermions where distance scales of order 10^{-18} m are being probed. A national research programme therefore supports a range of different research interests, both at national facilities and at international laboratories. One of the strongest aspects of Canadian subatomic physics has been its ability to remain a focussed research programme as it evolves and responds to scientific opportunities in the context of limited resources and infrastructure.

The subatomic physics research community recognises the need to develop strong efforts in a relatively small number of projects, while at the same time supporting a sufficiently broad scientific effort that successfully addresses the most important open questions. Thus, the current programme consists of a small number of large collaborations of Canadian physicists, such as the OPAL, ZEUS and ATLAS projects that are based at international laboratories, and a somewhat larger number of smaller efforts that consist of a few researchers operating mainly at national facilities such as SAL and TRIUMF. We believe that the number of separate projects has been approximately correct, noting that Canadian physicists have made significant contributions to the largest projects and have had a direct impact on the success of these efforts. The balance between finite resources and an intellectually active and diverse research frontier has to be continuously monitored. This has been achieved by the consistent application of stringent peer review by the GSC, whose membership has been dominated by internationally recognised Canadian and foreign scientists. Periodic long range planning has also helped maintain this balance and continues to be strongly supported by the researchers.

It has been noted that the future subatomic physics programme may become too focussed if funding for some new initiatives is not provided. In particular, the current Five Year Spending plan developed by the 1997 grant selection committee has essentially no funding for relatively modest new initiatives, as discussed in the previous section.

We also note that the question of overall balance across the subdisciplines of subatomic physics was addressed carefully by the Fenton committee, which concluded that:

> "The committee is confident that within the guidelines of our recommendations an outstanding, broadly-based scientific programme in subatomic physics will continue to prosper and evolve into the next century."

We still agree with this conclusion, although with the reservations expressed above concerning the overall level of funding being insufficient to obtain maximum scientific impact from the ongoing programme, and the lack of funding for new initiatives.

Recommendation 11 *The current balance of diversity versus focus within the subatomic physics programme should be maintained by future grant selection committees.*

7.4 Granting Mechanisms

NSERC has recognised the unique nature of this field by providing unique mechanisms to support subatomic physics. The Project Grant is aimed at specifically supporting a large group of investigators collaborating on a specific project, while the Major Facilities Access Grant provides support for national facilities that are used by a number of different collaborations.

The introduction of the Project Grant has also created some problems. It does not allow researchers to use funds from Project Grants for R&D on unrelated projects. It also places a greater onus on the collaborations to work together to determine how funds should be allocated between the participating researchers.

7.5 Support for Subatomic Physics Infrastructure

The community values the infrastructure support for subatomic physics very highly, and it is considered a significant strength of the programme. The infrastructure is provided in several forms: via TRIUMF through its expanding role as an infrastructure centre, through the Major Facilities Access grants that support technical infrastructure at the universities, through the IPP research scientist programme, and through other NSERC funded organisations such as the Canadian Microelectronics Corporation (CMC).

The recent reduction in the IPP research scientist complement from eight to seven scientists is, however, a concern. These staff have an enormous impact on the success of the IPP programme and the loss of even one position is very detrimental. The infrastructure resources available from TRIUMF and the coordination of these resources is another area of concern.

7.6 Support for National Laboratories

The five-year funding plan for TRIUMF, initially approved in 1996, is a significant step forward in funding of subatomic physics in Canada, as it has allowed the field to plan more effectively for facilities and experiments that have time horizons that span decades.

However, in the last year, decisions have been made to shut down two national centres for subatomic physics research, SAL and TASCC. These decisions (one recommended by the Fenton report and the other made unilaterally by AECL) are expected to have significant negative effects on subatomic physics research. They curtail the research opportunities for Canadian scientists and students, and reduce the subatomic physics infrastructure available in Canada. TRIUMF soon will be the only national subatomic physics laboratory.

The closures of these facilities will be a significant blow to the community, and in the case of TASCC, one that came with essentially no consultation with the research community. Currently, there are attempts underway to preserve as much of the TASCC programme as possible by relocating detectors such as the 8π spectrometer and the Canadian Penning Trap Mass Spectrometer to offshore facilities. However, these moves will not mitigate the sizeable negative impact on the productivity of the scientists involved.

7.7 Long Range Planning

Long range planning is crucial to a field with such long term projects as exist in subatomic physics. Although this task is recognised universally as being fraught with difficulties, the most recent exercises have produced plans for the programme that were credible both within the scientific community and with the funding agencies. Much of the community feels that holding similar exercises at regular intervals will be very productive.

The support for the conclusions of the Fenton Report have been surprisingly strong, given the rather draconian cuts it recommended in most of the funding scenarios. The fact that it was felt to have consulted successfully the community and addressed its charge from the funding agencies are perhaps the most important reasons why its conclusions have met with broad acceptance within Canadian subatomic physics.

Recommendation 12 *NSERC should continue to support community-wide long range planning as the basis for its long-term view of the development of the field. Planning exercises, with active participation of the GSC, should take place on the three to five year timescale.*

7.8 Coordination Between Funding Agencies

The community noted in the course of our review an unhealthy lack of coordination between Canadian funding agencies that support subatomic physics. Two cases in point make this clear. The first is the planned withdrawal of AECL from basic research at its Chalk River facility. This had the apparently unintended effect of reducing infrastructure support for the SNO experiment and the loss to the subatomic physics programme of considerable scientific personnel. The second example is the decision by the government to fund a Canadian contribution to the LHC in the absence of a funding plan for the NSERC supported scientific programme that could take advantage of this investment. This problem was subsequently left to be addressed in the long range planning exercise, creating a situation where the accelerator and detector investments were not well coordinated.

In these cases and many others, senior researchers have been forced to expend considerable time and energy to understand what options are open to their scientific collaborations, and how best to proceed. Better coordination and communication between the scientific community and the funding agencies will be clearly of significant benefit.

Recommendation 13 *The Canadian government should improve coordination between the various agencies that sponsor subatomic physics research. In particular, policy options that have an impact on specific elements of the programme should be discussed and developed in consultation with representatives of all the relevant agencies.*

8 The Vision for Canadian Subatomic Physics

Subatomic physics deals with very fundamental problems in physics, related to our understanding of the elementary forces and particles in nature, and the novel phenomena arising in many-body nuclear systems. It also has allowed us to approach at a microscopic scale the behaviour of the universe at its earliest moments. The field is highly dynamic with a long history of rapid theoretical and experimental progress. Subatomic physics research often requires accelerators and large complex detectors. The size and scope of these facilities demand extensive long range planning. Consequently the community has a well established vision of where it wants to go in the future. As scientists in an area of fundamental research, our thoughts are on identifying the basic questions of human curiosity that are within our technological reach. The Canadian community has selected key experiments with the criteria that they address the most important physics, they have a high probability of success and that Canada can make a large impact.

The choices of the community, summarized below, essentially define our vision of subatomic physics. A substantial amount of effort has gone into creating this Canadian programme and we will continue to examine critically our choices as the field evolves. In order to accommodate this new programme, the field has already made the necessary decisions to bring to closure several ongoing research efforts.

Arguably the most important unknown feature of the Standard Model of subatomic physics is the origin of particle masses. A direct search (the ATLAS experiment) at the energy frontier for the proposed Higgs bosons is one of the top priorities. The high energy collisions studied by ATLAS are also the best place to look for new physics that would arise from extensions to the Standard Model that are required to explain many of the mysteries that this model does not address.

Subatomic physics has an intimate relationship with cosmology and astrophysics. Fundamental questions in subatomic physics arise from astrophysical considerations. It is now possible to make terrestrial measurements that test our understanding of stars and the first moments of the Big Bang. Canada is involved in four projects inspired by questions posed by astrophysics. Two major projects, SNO and ISAC, are under construction in Canada. They are excellent examples of the interdisciplinary research that bridges the gap between subatomic physics, astrophysics and cosmology. Studying time reversal invariance (the BaBar experiment) is important to understand the preponderance of matter over anti-matter in the universe. Searching for new forms of matter such as quark-gluon plasmas (the PHENIX experiment) provides insight into the earliest moments of the universe.

TRIUMF will continue as the national facility to carry out important experiments while serving as the infrastructure facility for the discipline. It will lead many aspects of the applied program, including cancer treatment, condensed matter physics using muons and medical treatment and diagnostics using radioisotopes.

Canadian subatomic physicists continue to develop world class facilities in Canada. At the same time, global facilities have to be built and exploited in an international cooperative effort. Plans are being made to construct a Large Hadron Facility in Japan and the Next Linear Collider at some location in the world. International collaboration on major facilities ensures the brightest young minds in Canada stay on the cutting edge of subatomic physics at the best facilities in the world.

The Canadian subatomic physics community is dedicated to providing the most challenging opportunities for its students and young researchers as a means of enhancing Canada's ability to exploit new technologies and new knowledge emerging from its research. Interdisciplinary research and spin-off ventures follow from pursuing excellence without regard to the traditional boundaries of the field. In particular, opportunities are seen in health sciences, biology and the environment.

The vision of the subatomic physics community is expressed in the plan we have outlined to focus on the most important and pressing issues in our field.

Acknowledgements

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Appendix A: Summary of Recommendations

Recommendation 1 *The level of funding for theoretical subatomic physics recommended by the Fenton committee should be maintained (approximately 10% of the envelope, or $1.73M), and in a context where additional funding is made available, increased support of the theoretical programme should be considered.*

Recommendation 2 *NSERC should allow the GSC to "forward borrow" funds to accommodate variations in capital funding requirements of the programme. A specific policy should be adopted to enable the GSC to understand the constraints this presents and to ensure that NSERC staff can manage such forward-borrowing.*

Recommendation 3 *In a scenario where up to 15% of additional funding is made available to the subatomic physics GSC, funding should be provided to one or more of the new initiatives that have been proposed by the community. Potential projects are the advance of the ISAC physics programme, enhancement of the scope of the Canadian involvement in ATLAS, and the use of the SNO facility for Dark Matter or supernovae searches.*

Recommendation 4 *The number of research scientists supported by NSERC be maintained at the current level, and in the context of additional funding the number of research scientists should be increased.*

Recommendation 5 *TRIUMF's role as an infrastructure centre for Canadian subatomic physics research should continue to be supported.*

Recommendation 6 *The NSERC GSC should maintain the support of subatomic physics infrastructure and the technical and engineering personnel funded by Major Facilities Access grants. Continued support should also be provided to computer networks used by subatomic physics through the HEPNET project.*

Recommendation 7 *NSERC should promote University-based technology transfer programmes, drawing on the experience gained at national laboratories.*

Recommendation 8 *NSERC should continue to ensure that research grant applications that fall within the jurisdiction of two or more grant selection committees be adequately peer reviewed and that potential disincentives (such as transfer of grant funds from one committee to the next) not prejudice the review of such grant applications.*

Recommendation 9 *The subatomic physics community should develop a coherent public outreach and education programme, building on the existing efforts at TRIUMF and other institutions. NSERC and CAP could play a coordinating role in this effort.*

Recommendation 10 *The NSERC GSC should allocate approximately 5-10% of the envelope to new initiatives, beyond what is currently outlined in the GSC Five Year Spending Plan. This should be phased in as rapidly as possible, but consistent with the longer term financial constraints faced by the GSC.*

Recommendation 11 *The current balance of diversity versus focus within the subatomic physics programme should be maintained by future grant selection committees.*

Recommendation 12 *NSERC should continue to support community-wide long range planning as the basis for its long-term view of the development of the field. Planning exercises, with active participation of the GSC, should take place on the three to five year timescale.*

Recommendation 13 *The Canadian government should improve coordination between the various agencies that sponsor subatomic physics research. In particular, policy options that have an impact on specific elements of the programme should be discussed and developed in consultation with representatives of all the relevant agencies.*

Appendix B: Terms of Reference

We list below the full terms of reference of this review. We also list the section numbers where discussion of the specific item can be found.

In this charge, Canadian Physicist Members (CPM's) are the members of the four research subcommittees. The Assessors are the international reviewers who provide written assessments of the work described in this report.

1. Survey current and planned academic physics activity within Canada with enough detail on the nature of the work and on the indicators of its excellence to permit proper assessment by the Subcommittee's Assessor members.

   This is done primarily in Section 3. Some additional historical information is provided in Section 2.

2. Highlight what the CPM's believe to be current areas of Canadian strengths and weaknesses on an international scale, and how they fit in with the ongoing evolution of the field. Weaknesses could include important or emerging areas needing more emphasis, or areas where less emphasis seems appropriate. While the identification of such areas could assist future GSC deliberations, it is not intended to define areas which GSC's would be constrained not to support.

   The strengths and weaknesses of the programme are highlighted in Section 7, although the discussion in Section 5 is also relevant to this topic.

3. Make recommendations concerning (i) particular areas of focus for the future, (ii) ways to ensure that such focus does not unduly diminish research diversity and risk-taking.

   This is discussed in the Fenton Report and in Sections 3.2, 7.1 and 7.2.

4. Attempt to establish a consensus in the community (within parameters acceptable to NSERC) regarding how best to use available funding. This should include a detailed consideration of the proper level of selectivity appropriate to the subdiscipline, and of means to balance any increased geographical, institutional or subdiscipline concentration with the need for continuing diversity. In the context of an increased emphasis on industrial partnerships, ways to assist those in the less industrially developed areas of Canada to establish such partnerships should be considered.

   This task relates to broad principles of 'how much selectivity,' 'how much concentration,' etc., rather than to the support to be given to specific areas. However, means should be suggested by which GSC's can take these principles into account. The reasoning behind the consensus should be clearly stated.

   This topic was also handled in detail in the Fenton report. However, discussion relevant to this issue can be found in Section 5.

5. Provide NSERC with the community's views on how NSERC may better encourage (i) risk-taking, (ii) spin-off activities, (iii) communication of the results of research to the public and to other disciplines, and (iv) physics participation in interdisciplinary research.

   This is discussed in Section 6.

6. Evaluate the interactions and impact of Canadian physics research on other disciplines, and identify means of enhancing them.

   This is discussed in Section 6.

7. Review whether the overall health of Canadian physics or of the subdiscipline would be enhanced by a major collaborative effort across physics boundaries and/or between physics and other disciplines, and if so identify that effort.

   The Subcommittee felt that the current treatment of subatomic physics as a single, coherent programme was an appropriate approach (see Section 3.1). Other aspects of interdisciplinary work are described in Section 6.

8. Provide the Subcommittee's views on the following questions. If 15% additional NSERC funding of the discipline were available, what would it be used for? If 15% less were available, what would be the responses and what would be the effects? These are not necessarily research quality judgements, but might include urgency or other considerations.

   The Fenton report examines the effects of these various scenarios and a summary of their recommendations is provided in Section 2.4 and 5.1.3. Discussion of the effect of recent reductions in funding can be found in Section 7.1.

9. Write a preliminary report on the findings, and (after iteration with the Canadian community) submit the final report to review by the Assessor members of the Subcommittee.

10. Develop a "Vision Statement" for the subdiscipline, according to criteria to be specific by NSERC in accordance with the requirements of NSERC Council.

    See Section 8.

Appendix C: Abbreviations and Acronyms

AECL Atomic Energy of Canada Limited

CAP Canadian Association of Physicists

CDF Collider Detector at Fermilab

CEBAF Thomas Jefferson National Accelerator Facility or Jefferson Lab (formerly the Continuous Electron Beam Accelerator Facility or CEBAF)

CERN European Centre for Research in Nuclear Physics

CHAOS Canadian High Acceptance Orbit Spectrometer

CMC Canadian Microelectronics Corporation, Kingston, Ontario

CP Charge-parity

CRL Chalk River Laboratories

CRPP Centre for Research in Particle Physics, Ottawa, Canada

DESY Deutches Electronen-Synchroton, Hamburg, Germany

DNP Canadian Association of Physicists Division of Nuclear Physics

DIS Deep-inelastic scattering of high energy leptons and nuclei

GSC NSERC Grant Selection Committee

Fermilab Fermi National Accelerator Laboratory

HERA Electron-proton collider located at the DESY laboratory

HERMES HERA Measurement of Spin

IPP Institute of Particle Physics

ISAC Isotope Seperator and Accelerator

LEP Large Electron Positron Collider at CERN, Geneva

LHC Large Hadron Collider at CERN, Geneva

MSW Mikhailov-Smirnov-Wolfenstein effect, a theory that explains the observed deficit of solar neutrinos using a neutrino-oscillation model.

OPAL Omni-purpose Apparatus for LEP

QCD Quantum Chromodynamics, the theory of the strong interaction

RHIC Relativistic Heavy Ion Collider

SAL Saskatchewan Accelerator Laboratory

SAP Subatomic Physics

SNO Sudbury Neutrino Observatory

TASCC Tandem Accelerator Superconducting Cyclotron at Chalk River

TRIUMF Tri-University Meson Facility

Appendix D: Subatomic Physics Research Subcommittee

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