Canadian Subatomic Physics Theory:

Role and Needs, 2006-2016

Brief of the ad-hoc long-range planning committee

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1 Introduction

Every 5 years, the NSERC granting agency asks the communities it serves to prepare a long range planning brief, outlining their needs and goals for the coming 5 years. This year NSERC has requested that the brief also discuss a longer time horizon, 5-10 years, and that it specifically focus on three possible scenarios:

- A substantial increase in funding, of 100% of current funds over the time frame of the report.
- Constant funding or funding increases only to match inflation.
- A significant reduction in funding, such as a 20% cut with no corrections for inflation.

The subatomic community, served by the GSC-19, is itself composed of subcommunitites with quite distinct needs. Therefore, subcommittees have been struck to present briefs covering the needs and plans of each subcommunity. This is the brief of the ad-hoc subatomic theory committee.

Unlike our experimental colleagues, subatomic theorists are not generally part of large and long term collaborations. Autonomous individuals plan their own research agendas with little community-wide coordination. Research plans change as events dictate, often on yearly or few yearly timescales. Even in those subdisciplines which are equipment intensive and involve long term, named collaborations (such as lattice gauge theory), the collaborative efforts are smaller, looser, and shorter time scale than in subatomic experiment. Therefore, the nature of long range planning in the theory community is different than in the experimental community. For this reason, this document will contain no specific prioritized lists of projects which the theory community should attack in the coming 5 to 10 years.

Instead, we will try to put subatomic theory in the context of the subatomic community as a whole, to survey its status and research highlights, to explain where theory funding goes to (primarily to training of HQP). There are some issues which the community needs to plan for in the coming years, particularly the commissioning of the LHC and of the ISAC II facility. Also, there is consistent interest within the community in a theory centre; we discuss the advantages of such an institute and the forms it might take. We close by discussing how each of the funding possibilities would affect the theory community.

2 The Role of Theory

The role of theory is crucial in all areas of subatomic exploration. Theory and experiment are tightly intertwined: theoretical ideas motivate new experiments and help tell experimentalists what to look for; and theoretical work is also needed to understand and interpret the results of experiments. Theory, in turn, relies on experiment to test its predictions and ideas, and in some cases to show that none of those ideas are correct and the theory must head in a different direction.

New theoretical ideas, often coming from formal developments and model building, provide targets for experimentation. Examples of such ideas are the Higgs mechanism, supersymmetry, and extra dimensions. Discovering any or all of them has become the major goal of experimental efforts at the high energy frontier.

At lower energies, high-precision measurements can also serve to discover new physics, if supplemented by detailed studies of theoretical predictions. Phenomenological predictions of theoretical models inform high-sensitivity searches, such as rare decays and symmetry-breaking properties of particles like the electric dipole moments. Of course, the flow of inspiration goes both ways. Even formal theoretical physics ultimately has to rely on experiments for verification.

Theoretical calculations are also essential in converting the results of experiments into statements about model parameters. For instance, high-order QCD calculations are needed to relate most new physics signals at the LHC to the experimental signatures. Similarly, advances in lower energy QCD theory such as heavy quark effective theory and soft collinear effective theory can help to relate experimental observables in flavor physics to the theory parameters (such as CKM parameters) under investigation.

There is an important need to engage in fundamental research for its own sake, which does not directly relate to experiment in any tangible way at the moment. It serves more to focus and correlate our present ideas of the state of the physical laws, and it serves to discover these laws. Fundamental research is what gives rise to a revolution of ideas, changing the way we look at the universe. It also develops the tools which are so often of relevance later in wringing predictions from physical theories. It is important to have a strong program of fundamental research within the subatomic physics community, even beyond the short-term connection with experiment.

Clearly, theoretical and experimental subatomic physics are complementary, and cannot properly develop without one another. Theoretical investigations are stimulated by past and current experiments, help interpret them, and are crucial for defining future experimental projects. This interchange does not necessarily have to go on within a single institution, or even within a single country. So why shouldn't Canada let other people do theory and concentrate on experiment? One reason is that theorists and experimentalists also profit from day-to-day interchange, with the theorists typically acting as a resource to explain the theoretical ideas and their implications to the experimentalists (not only new ideas, but also to clarify the meaning and predictions of existing theory), and with the experimentalists clarifying for the theorists what is known experimentally and what is and is not possible to verify experimentally within existing experimental frameworks. This kind of exchange *can* go on remotely via e-mail or telephone between participants in other countries, but is far more efficiently conducted face-to-face.

Subatomic physics has strong overlaps with other areas of physics, notably atomic physics, condensed matter physics, gravity and astrophysics. These interdisciplinary contacts are mutually enriching and inspiring, and sometimes result in creating new areas of research such as astroparticle physics. Methods developed in subatomic physics have often revolutionized other areas of physics. For example, Feynman diagrams and techniques of evaluating them, developed in particle physics, have been instrumental in condensed matter and atomic physics. The understanding of renormalization grew out of an interaction between high energy-physics and the study of critical phenomena in condensed matter physics. It is now being applied to nuclear physics. There are many common themes between nuclear and atomic or condensed matter theory, since all investigate strongly interacting quantum many-body systems. For example: How does the structure of matter change with its composition? What is the many-body physics of complex and collective phenomena? How are shape transitions in nuclei and the crust of neutron stars related to frustrated systems and the phase diagram of asymmetric matter? How does matter respond to external probes? What are the large-scattering length features in nuclear structure, resonant nuclear reactions and neutron matter?

At universities, subatomic theorists play a very important role in teaching. They offer advanced courses that stimulate students' curiosity and provide essential training for experimental as well as theoretical students. Subatomic theory attracts excellent graduate students because it is so intellectually appealing. Those students often go on to do research in other areas, including experimental physics. The time they invest in theoretical studies pays back through the skills they acquire, particularly computational knowledge and analytical problem-solving techniques.

It is important to view theory and experiment as strongly complementary. If one community is not healthy, it will damage the health of the other. Similarly, keeping each side healthy will enrich the other.

3 Status of Theory in Canada

At this time there are 74 subatomic theorists in Canada who hold NSERC discovery grants. This is a diverse field, and the environments they work in are also diverse. Most are in the large research universities and at TRIUMF, typically in groups with close contact with experimentalists. However, a central feature of the subatomic landscape in Canada is that many of the researchers are in small, often remote or isolated, institutions, often as the only subatomic theorist, or even the only subatomic physicist, at the institution.

The theory community has been experiencing a renewal recently, with a number of new hires, see table 1. These hires have more than replaced the number of retirements, so that over the last 5 years the number of subatomic theory grants has risen by about 5. This process is expected to continue in the next 5 years; there are currently searches at UBC and McGill for subatomic theorists, and searches at Alberta and Simon Fraser which will include subatomic theory in the search category. We expect the community to continue to grow gradually, by perhaps one member per year.

Unlike the experimental community, theorists are not generally part of large, long term collaborations. While few theorists work alone, they typically collaborate in smaller groups, and these collaborations break up and recombine, sometimes over several year timescales and sometimes much faster. Over a career, a subatomic theorist will typically work on several different kinds or branches of subatomic theory, sometimes with a foray out of subatomic theory altogether. This system is appropriate for the field, because the fixed cost investments

Year	Theorist	Institution	Approximate area
2000	Amanda Peet	Toronto	Formal (string)
2000	Vladimir Miransky	Western	Field theory
2000	Andrzej Czarnecki	Alberta	Phenomenology
2001	Sangyong Jeon	McGill	Nuclear theory
2001	Erich Poppitz	Toronto	Formal
2001	Moshe Rozali	UBC	Formal (string)
2002	Guy D. Moore	McGill	Field theory
2002	Kentaro Hori	Toronto	Formal (string)
2002	Baskhar Dutta	Regina	Phenomenology
2002	Mark van Raamsdonk	UBC	Formal (string)
2002	Maxim Pospelov	Victoria	Phenomenology
2003	Alex Buchel	Western	Formal
2003	Todd Fugleberg	Brandon	Field theory
2004	Robert Brandenberger	McGill	Cosmology
2004	Jaume Gomis	Perimeter	Formal (string)
2004	Svetlana Barkanova	Acadia	Nuclear theory
2005	Keshav DasGupta	McGill	Formal (string)
2005	Heather Logan	Carleton	Phenomenology
2005	Freddy Cachazo	Perimeter	Formal (string)
2005	Justin Khoury	Perimeter	Cosmology
2005	Adam Ritz	Victoria	Phenomenology
2005	Achim Schwenk	TRIUMF	Nuclear theory

Table 1: Recent arrivals to Canadian subatomic theory. The "approximate area" column should be read with caution because of the flexibility of theorists and the difficulty of categorizing certain work.

are much smaller than in experiment. Some sub-branches, such as lattice gauge theory or high order phenomenological calculation, are more given to larger and longer term collaboration, and may even possess named collaborations or working groups. Other areas, particularly in formal theory and model building, are much more fluid.

This difference between the organization of the theory and experiment communities means that long range planning plays less of a role in theory than it does in experiment. Theorists are more flexible to pursue a new idea or try to understand new data on a short time scale. However, we must plan ahead enough to make sure that the community has the favorable environment and available resources to function effectively.

4 Research highlights

To clarify better what the subatomic theory community is doing in Canada, we give some highlights of recent topics and recent progress by the community.

4.1 Formal Theory

Efforts in formal theory have recently increased dramatically in Canada, especially regarding string theory and related efforts. Canada is becoming an international centre for string theory, following a period of concentrated efforts in hosting workshops, conferences, summer schools and the large international conference "Strings 2005."

String theory is primarily a theory of quantum gravity, which provides a consistent quantization of gravity, along with all of the other degrees of freedom of the standard model. In the near future, a large number of expected theoretical and observational developments will require the interaction and comparison of gravitational physics (as relevant to cosmology) and particle physics. String theory is in a unique position to shed light on that interface.

The recent developments in string theory have stressed its unique role as a quantum theory of gravity. Most significantly, string theory has provided deep insights into the quantum mechanics of black holes. As was known since the 1970's, black holes exhibit thermodynamical behavior and are characterized by entropy, temperature, *etc.* The statistical mechanics giving rise to this behavior had to await the understanding of black hole microscopic degrees of freedom. The counting of degrees of freedom to determine the entropy of black holes assures us that string theory contains the correct microscopic degrees of freedom. Other, more detailed calculations assure us that it also has the correct dynamics for these degrees of freedom.

The study of black holes in string theory has resulted in the AdS/CFT correspondence, which is an exact quantum correspondence between a gravitational string theory and a lower dimensional field theory. This highlights once again string theory as the unique framework relating gravity and particle physics. Indeed, duality between conventional (albeit strongly coupled) field theories and theories of quantized gravity suggest there is no deep distinction between the two, and is useful to shed light on both sides of the correspondence. Several groups in Canada, including the ones in Perimeter and UBC, have worked to extend the correspondence and understand it better.

Given the upcoming new era of experiment in high energy physics, a lot of the effort has been directed in making the connection between these theoretical achievements and future experiments. One such connection utilizes the efficiency of the string theory language in dealing with strongly coupled quantum systems. One avenue of research has been the understanding of gauge theories in different regimes. This is relevant for better understanding of confinement, building models of SUSY breaking and technicolor using strong dynamics, and calculating QCD scattering cross-sections (using twistor space methods) as relevant for the upcoming LHC. These efforts were spread throughout Canada in all the formal HET groups.

String theory has also inspired phenomenological models for cosmology and particle physics based on branes (braneworld scenarios). The idea is that standard model fields live in four dimensional hypersurface in a higher dimensional space, whereas gravity moves in the bulk of these dimensions. This has been inspired by constructions in string theory such as D-branes, orbifolds, and extra dimensions. As models for particle physics they have been amazingly inventive, as they put many classic problems in high energy physics and cosmology in a new perspective. The effort to embed these scenarios in a consistent string theory context is expected to yield all the benefits of having a constrained theoretical framework which has many cross checks between gravitational and particle physics phenomena.

In addition to the study of aspects of string theory, efforts along more traditional lines of formal particle theory continue to make progress throughout Canada. These include formal approaches to field theory, the study of topological defects and their applications to cosmology and particle physics, and much more.

In the near future we anticipate an effort to make string theory and other formal theory relevant for experiment, and to interact more with other aspects of particle physics. Subatomic theory at large will benefit from a large and vibrant community of formal theorists that exists in Canadian universities.

4.2 Phenomenology

“Phenomenology” in particle theory refers to an extremely broad program of research. Roughly speaking, particle phenomenology has been taken to mean research which has fairly solid connections to current or future experiments. Phenomenology thus covers a vast range of research, including Beyond the Standard Model model-building, QCD, flavour physics, neutrino physics, collider physics and particle cosmology. In many areas (i.e. braneworlds), the distinction between “formal theory” and “phenomenology” is not particularly well-defined. Canadian theorists are active in all of these fields, and indeed many theorists are active in several.

All of these fields are expected to remain extremely active over the next five years. The start of the LHC program will be the single most important experimental factor driving research, but a host of other experiments in neutrino physics, flavour physics and cosmology will also play major roles, and as a result the interplay between theory and experiment is expected to become stronger.

Despite its successes, the Standard Model of Particle Physics has a number of shortcomings which suggest that new particles and forces must exist at the TeV energy scale - the major unresolved issues are the mechanism of electroweak symmetry breaking, and the origin of "flavour" physics (the patterns of masses and couplings of the elementary particles). Dynamical symmetry breaking, supersymmetry and models with extra dimensions are a few of the most popular frameworks to study these questions, and research in this are focuses on constructing realistic models, understanding new mechanisms for generating both flavour and symmetry breaking, and studying the experimental implications - both in the lab and cosmological - of these scenarios. Cosmological measurements frequently constrain new models of Physics; conversely, particle theory provides models to understand cosmological issues such as dark matter, the cosmological constant, inflation and baryogensis. The Canadian theoretical community has particular strength in this area, including groups at Victoria, UBC, Toronto, McGill and Perimeter.

Studying the signatures of Beyond the Standard Model scenarios at colliders is a field in itself in which the Canadian community is active - Carleton in particular has a number of theorists active in this area. This has been a very active field over the past decade, as strategies for studying new physics at the LHC have been developed. Experimentally viable signatures for models of new physics must be determined, and the corresponding Standard Model signals understood. Whatever is found at the LHC, determining the implications of the measurements for New Physics will require considerable theoretical input. At the same time, similar studies will be required for the proposed International Linear Collider.

High precision flavour physics - the study of transitions between different flavours of quarks and leptons - provides a window on the TeV scale which is complementary to that obtained at high-energy colliders. In particular, rare B and K decays are highly sensitive probes of new degrees of freedom, which enter through virtual (loop) contributions of new particles to these observables. The study of the weak interactions of quarks is unavoidably complicated by the fact that quarks do not appear as free particles, but rather are bound up in hadrons by the strong interactions, whose properties are not currently calculable from first principles. Theoretical efforts in this field have therefore focused on strategies to disentangle the short-distance physics of interest from the long-distance hadronic physics, and the determination of clean signatures of new physics. A number of Canadian theorists, particularly at Toronto, Montreal and Alberta, have been extensively involved in this program. In the short term of the next several years, the B factories at SLAC and KEK will continue to collect precision data, and theoretical techniques will have to continue to improve. However, in the era of the LHC, flavour physics will continue to be a crucial ingredient to understanding New Physics. It is expected that the LHC will discover new degrees of freedom at the TeV scale. However, indirect precision experiments will be crucial to give information on the couplings of these new degrees of freedom. Rare decays, CP violation and precision measurements will be the only way to measure the couplings of these degrees of freedom, and hence to distinguish between different models of New Physics. Some of the theoretical techniques which have been developed have been applied to other multi- scale problems, including nuclear and atomic physics.

Of course, theorists in all of these subfields of phenomenology interact with theorists in the other areas of research discussed in this report. Lattice gauge theory has strong implications for precision flavour physics, as does formal theory for model building, cosmology and even collider physics.

4.3 Lattice gauge theory

Recently there has been a renaissance in lattice gauge theory, which Canada has been a part of.

Two main difficulties have plagued lattice gauge theory since shortly after its invention. Both have to do with the numerical difficulty of handling quarks. First, the inclusion of the vacuum effects of quarks is extremely costly. It is especially costly if the quarks are light. Therefore it has been common to perform computations in the "quenched approximation," which means neglecting entirely the vacuum effects of quarks (the $q\bar{q}$ sea). Second, even if sea quarks are not included, handling quarks as external or valence states becomes numerically costly and encounters other serious difficulties if the quarks are light. The result is that the u, d, and s quarks have typically been included at unrealistically heavy masses. Unfortunately, the extreme lightness of these quarks, especially the u and d quarks, seems to play a central role in real world QCD. Also, the quenched approximation introduces systematic errors, thought to be at least at the 10% level, and in some cases it leaves the correct computational approach ambiguous.

Recent advances in action improvement (highly improved staggered fermions) have made it possible to include the vacuum fluctuations (sea quark effects) for quite light quark masses at a fraction of the numerical costs needed by previous techniques. Together with improvements in computer power, this has allowed unquenched (dynamical fermion) calculations at close to the physical values of the quark masses, eliminating the uncontrolled systematic errors associated with the quenched approximation. These improvements have largely been pushed through by the HPQCD (high precision QCD) collaboration, a collaboration between US, Canadian, and British theorists. The Canadian contribution (Howard Trottier at Simon Fraser and Richard Woloshyn at TRIUMF) has played an important role in the collaboration, for instance, in performing high order perturbative calculations needed in constructing improved actions and operators. The HPQCD collaboration has achieved few percent determinations of the hadron spectrum, and has recently produced greatly improved determinations of α_s, the light quark masses, and heavy meson decay constants and form factors. This has sharpened the determinations of several parameters of the standard model, and will be particularly important in understanding the physics of flavor and CP violation.

While it is still not possible to conduct lattice simulations with quarks as light as the physical u and d quarks, recent theoretical improvements mean that we better understand how to perform extrapolations in quark masses, from lattice data with a few unphysical values of m_u and m_d towards the physical values. The techniques involve extensions of chiral perturbation theory to handle the effects of the lattice discretization. Canada has had a role in this development, for instance, in the work or Randy Lewis at Regina. Between better understanding of the chiral extrapolation and being able to start closer to the chiral limit (lighter quark masses), the systematic errors caused by simulating at unphysical quark masses have been greatly reduced. This work, like the work developing and applying lattice improvement to make precision lattice calculations, is ongoing.

4.4 Intermediate Energy Physics and Hadron Structure

At present, lattice QCD calculations are possible for limited aspects of hadron structure. Therefore, many of the predictions in hadron physics and our understanding of intermediate-energy experiments comes from QCD-inspired models, such as the constituent quark model (where much of the early work was done in Canada by Isgur and Karl), QCD sum rules (Maltman, York) and chiral soliton models. The work on the constituent quark model is continuing with recent developments on charm mesons (Godfrey, Carleton). The observation of the h_c, for instance, is an important test of QCD calculations and provides constraints on models of quarkonium spectroscopy. In addition, all the above models have been applied to the study of the controversial pentaquark. In comparison with future lattice QCD calculations, these models will provide valuable insights into what are the dominant quark and gluon configurations in the lattice simulations.

An example for the support of the hadronic structure experiments has been the work on electromagnetic radiative corrections and two-photon exchange contributions (Blunden, Manitoba). The Rosenbluth separation results for the electromagnetic formfactors of the nucleon disagree significantly with those obtained from recoil polarization, and this is largely due to the two-photon exchange contribution. Many more examples for a successful theory-experiment interaction can be found in the nuclear physics brief.

4.5 High temperature/density QCD and nonequilibrium theory

Canadian theory has played a continuing and growing role in understanding many-body and nonequilibrium subatomic theory. Currently, there are two main thrusts in this field: better understanding of QCD under extreme conditions of density and temperature, and better understanding of very early universe cosmology, particularly the end of the inflationary epoch.

In the past few years, the commissioning of the RHIC collider at Brookhaven has opened a new era in understanding QCD under extreme energy densities. The goal of the experiment was to create a Quark-Gluon plasma, a state of matter at extreme temperatures in which the quarks and gluons cease to be bound within hadrons but form a sort of "soup" of liberated partons. More broadly defined, the experiment is intended to determine the properties of nuclear matter as its energy density is made higher than has ever been explored previously. The experiment has led to a series of surprises. While it appears that the quark-gluon plasma has been produced, it does not seem to have quite the properties that were originally anticipated. In particular, the degree of collectivity of the plasma is far higher than anyone expected. The plasma flows like a nearly ideal fluid, rather than as a collection of weakly coupled particles. The spectra of the hadrons emerging from the heavy ion collisions has shown some unexpected features as well, with a dearth of high energy particles and an unusual difference in behavior between mesons and baryons.

The theory community has been struggling to understand these features and to predict how they will depend on energy, something to be tested both at RHIC and in the heavy ion program at the LHC, to begin in a few years (within the planning window). For instance, the group at McGill has been involved in understanding the fragmentation region of the heavy ion collisions, in making predictions of dilepton and photon production (soon to be tested experimentally), in trying to understand the energy loss which removes most of the highest energy hadrons from the final state, and in understanding the effect of the plasma on heavy quarks.

The other exciting venue for many-body QCD physics is conditions of extreme density. This area, possibly relevant for the physics of neutron stars, has seen a revival since the realization (by an expatriate Canadian, among others) that dense quark systems should exhibit a QCD analog of superconductivity, color superconductivity. The area of high density QCD has proven very rich, and has been pursued actively in Canada, for instance by Miransky at Western, who has explored the phase structure of high density QCD, and by Zhitnitsky at UBC, who has studied a number of issues related to high density and high isospin density QCD.

The Canadian theory community has also been involved in more formal studies of the behavior of weakly coupled plasmas near and out of equilibrium. Carrington and Kobes continue to improve the theoretical understanding of many-body theory, making the connection between diagrammatic techniques and kinetic theory. Another recent development is the realization that a nonabelian plasma such as the quark-gluon plasma can display plasma instabilities when it becomes highly anisotropic. This may help explain the collective behavior observed at RHIC. The exact role of plasma instabilities in a nonabelian plasma such as QCD is still not well understood and is a venue for active research.

Besides QCD, the other main venue for studying many body nonequilibrium physics in the subatomic community is in early universe cosmology. Of particular interest is the question, "how did inflation end?" The process by which the energy stored in the inflaton is transferred into other degrees of freedom, dubbed "reheating" or "preheating," was pioneered largely by two Canadian subatomic physicists, Lev Kofman at Toronto and Robert Brandenberger at McGill. The Toronto group in particular remains active in investigating this novel piece of cosmology and its possible cosmological signatures. There is also renewed interest in the formation of cosmic string networks after inflation, because of a beautiful interplay between the string theory and cosmology branches of subatomic theory.

4.6 Nuclear Theory

Over the past five years, there have been profound advances in nuclear theory based on effective field theory and the renormalization group. There are strong connections to the many-body physics of atomic and condensed matter physics, and nuclear physics is an essential part of astrophysics,and to the studies of fundamental symmetries.

The traditional difficulty in nuclear physics is that nuclear interactions are strong and model dependent. Different models for the strong repulsive cores lead to different behaviors at high momenta or high virtual energies. The optimal way to deal with these high-momentum parts is to convert the problem first to a low-energy effective theory more appropriate to the resolution at hand. Since short-distance details are not resolved at the energies under consideration, they can be replaced by simpler interactions, while maintaining all low-energy predictions. The renormalization group can be used to derive the low-momentum theory, and it was recently shown that all microscopic nuclear forces evolve to a universal low-momentum interaction (Schwenk, new hire at TRIUMF).

The low-momentum theory was also constructed systematically in chiral effective field theory. Effective field theory decouples nuclear physics from the more complicated problem of hadronic physics, while maintaining a direct connection to the underlying theory of QCD. Consequently, with nuclear effective field theory it is possible to address questions like: How would nuclear shell structure or nucleosynthesis change, if the up and down quark masses would be different?

Canadian nuclear theorists (for example Fearing, TRIUMF) have contributed significantly to our understanding of chiral perturbation theory. Effective field theories also provide the link to lattice QCD: Chiral perturbation theory is used to systematically extrapolate lattice results to the values of the physical quark masses (Lewis, Regina) and the low-energy constants of nuclear interactions can be determined using lattice QCD. The continuous advances in lattice QCD, for example full simulations with light quarks, make the latter a long-term vision for nuclear forces.

The long-term vision of nuclear many-body theory is a microscopic and predictive understanding of nucleonic matter under extreme compositions, temperatures and densities, on earth and in stars. This is closely aligned with the science program of the ISAC facility at TRIUMF. The observations to date indicate striking anomalous behaviour in rare isotopes, and the study of nuclei with extreme neutron to proton ratios will provide the missing links to our present understanding.

The nuclear many-body problem is extremely rich and complex. It spans eighteen orders of magnitude from nucleons to neutron stars and is ultimately based on QCD. A significant advantage of low-momentum interactions is that they can be directly applied to nuclear many-body systems with model-independent results and without uncontrolled resummations. For systems with $A < 100$ particles, prime approaches are exact shell model diagonalizations and the coupled cluster method, widely used in quantum chemistry. First applications of low-momentum interactions are very promising and can provide a microscopic basis for studies of the emergent phenomena of nuclei investigated at ISAC. For $A > 100$ particle systems, the method of choice is density functional theory, and its microscopic foundations are now well-understood. Advances for nuclear matter also motivate a program to derive the universal nuclear density functional from microscopic interactions.

In addition, Canadian theorists are making significant contributions to our understanding of nuclei using conventional interactions and methods. Towner (Queen's) and Hardy's work on superallowed β decay has been instrumental in the determination of the CKM matrix element V_{ud}, and is a shining example of how the understanding of the nuclear system impacts other areas of subatomic physics. This work is critical to the success of the Canadian experimental effort in superallowed β decay and shows the close collaboration between nuclear theorists and experimentalists. The work of Rowe (Toronto) on the nuclear shell model and collective phenomena integrates with the nuclear structure program at ISAC and provides an insight into critical phenomena in finite systems, complementary to the understanding gained in condensed matter physics for large systems.

There are several key advantages of nuclear effective field theory. In nuclear physics, many-body forces are inevitable. Chiral effective field theory makes it for the first time possible to systematically derive three and many-nucleon interactions, with weaker three-nucleon forces for low-momentum theories. As a result, calculations with microscopic three-nucleon interactions beyond the lightest nuclei are now possible. Three-nucleon interactions lead to particular density and isospin dependences, and experimental information from nuclei therefore provides significant constraints. Moreover, the coupling to electromagnetic/weak probes or parity-violating interactions can be consistently incorporated in applications of nuclear effective field theory to studies of fundamental symmetries.

Finally, the nuclear many-body problem shares many of the approaches and methods of atomic, condensed matter and high-energy many-body problems. All modern advances in nuclear many-body physics reach over physics subfield barriers: for example, effective field theory for few-nucleon systems and cold atoms, the coupled cluster method and density functional theory for nuclear and electronic structure, and the renormalization group approach of Shankar for superfluidity in neutron stars and low-dimensional Fermi systems.

5 Key Issues

All of the areas that subatomic theorists work in are evolving, but the commissioning of the LHC in the next few years will mark the most dramatic change in the subatomic environment in some time. We expect the LHC's commissioning to have a large impact on the field, and we have to start thinking about how to prepare for it now. Similarly, ISAC is having a large impact on nuclear physics.

There is also a way the theory community in Canada could change its own dynamics, by creating a theory centre. This idea has widespread but not universal support, and it remains to decide the exact form such a centre would take. We will discuss each of these three issues in turn.

5.1 LHC: challenge and opportunity

The startup of the Large Hadron Collider (LHC) in 2007 will mark the beginning of a new era in subatomic physics. This is the largest experiment in history, and is expected to present many new challenges and discoveries. After two decades of planning and construction, this powerful research instrument will start providing data on the highest energy frontier ever explored. This presents subatomic theory a unique opportunity to make an impact, if it can organize correctly to make use of its strengths.

Canada has a vibrant experimental community involved in ATLAS, one of the major experiments at the LHC. It needs theoretical support to fully benefit from the investment made in the construction of the detector and from efforts of collecting and analyzing the data. The discovery potential of the LHC will depend on our knowledge of standard model backgrounds that can mimic or mask signals of new physics. It also depends on our ability to predict the most likely new physics signals, since signal selection has to be built into an experiment at the level of the trigger; something unexpected cannot always be discovered by analyzing what comes out at the end if the right effort did not go into capturing it at the beginning. More effort should be encouraged towards improvement of understanding of those theoretical issues.

What the LHC represents to the high energy community, ISAC represents to the nuclear physics community. The commissioning of the ISAC-II facility in 2006 will open up the precision study of very short lived radioactive nuclear isotopes. Explosive astrophysical events like novae and supernovae involve short lived nuclear isotopes, and on earth these can only be studied at facilities like ISAC, where nuclear isotopes far from stability are produced. A main motivation for this work is to give theorists the experimental inputs needed to construct theories capable of describing accurately nuclei very far from stability. This will open up our ability to make accurate statements, for instance, about r-process nucleosynthesis, which was responsible for making many of the elements making up the

Earth.

A new experimental era will require a shift in priorities, and such a shift requires careful planning and appropriate resources. One obvious way to shift priorities, through hiring decisions, is controlled by the universities and is not at NSERC's disposal, unless it implements a theory program akin to the IPP program, which supports 8 research professors in high energy experiment. However, issues of communication and travel could be almost as effective in helping the community re-orient. It is difficult for a professor in isolation to substantially change their research program and enter a new field. To do so, it is best to develop collaborations with people already in the field. Also, for the workers in a field to develop a research plan and identify the most important problems to work on, it is useful to have gatherings such as conferences and workshops, and in some cases to form working groups on specific issues.

Naturally, subatomic physicists are organizing such conferences, working groups, and workshops all around the world. For the Canadian community to make an impact in LHC physics, it needs the travel resources to attend meetings and maintain collaborations around the world, and it needs available sources of funding for running conferences and meetings here in Canada. The best way to support travel is through individual (discovery) grants, because each individual researcher is in the best position to determine what meetings and collaborations are useful to them and to their students and postdocs. To organize conferences, workshops, and schools in Canada, it would be helpful if there were funding opportunities from NSERC to support such meetings. (To some extent the need for schools is already covered by a TRIUMF program, responsible for the Lake Louise schools. This should be made more systematic and more available across the full subatomic theory community.)

5.2 A Theory Institute in Canada?

The possibility of a national theory centre has been discussed in the Canadian subatomic community for several reasons, including the size of the country and the dispersion of the theoretical community, with many theorists being the only active subatomic theorist in their own department.

As already mentioned in the previous Theory Committee Report in 2000, an interesting example is the Centre for the Subatomic Structure of Matter (CSSM) at the University of Adelaide in Australia. The situation of subatomic theory in Australia has some similarities to that in Canada, with many researchers experiencing isolation in their home institutions.

CSSM played a successful role as a national institution and might serve as a useful model for what might be done in Canada to improve contacts and foster collaborations within the community. A similar initiative could perhaps motivate some people whose isolation makes them less active than they used to be.

Australian theorists regarded CSSM as a great resource and for many it was the main way (through topical workshops in particular) of meeting other members of the subatomic community. Everyone working in the field was an associate of CSSM, which tried to get them to visit at least once a year. Faculty and their students were invited (most expenses paid) to all workshops.

The role CITA in Toronto has played in Canadian astrophysics is an example closer to home. CITA maintains a large enough working group to achieve “critical mass” in astrophysics theory and experiment. It strengthens the community across Canada by encouraging and partially paying for visits, by conducting conferences and workshops, and by subsidizing a few postdoctoral positions in astrophysics and cosmology across Canada, with the requirement that the postdocs make visits to CITA. This encouragement of community members to visit CITA strengthens the centre and enhances collaborations between its remote associates. Recently, the Perimeter Institute has started to play a similar role for formal theory (especially loop quantum gravity and string theory) and quantum computation. In nuclear theory, extremely successful examples of such an institute are the INT, in Seattle, and ECT*, in Trento, Italy.

A theory institute in Canada could take several forms, from the minimalist to the ambitious:

- The minimal form would be a granting agency for schools and workshops. A governing board made up of Canadian theorists would consider proposals from Canadian institutions for hosting conferences, workshops, summer schools, and longer range meetings, which would then be organized and conducted by the proposing individuals and institution. Such a “floating institute” would have a low overhead, but it would not contribute much value added, instead acting as more of a clearing house and peer review system for event funding.

- Adding administrative support for meetings and conferences probably necessitates a fixed location. Therefore the next larger version of a theory institute would be a fixed-location institute with a director (who could be a faculty member at that institute) and secretarial support, committed visitor floor space and facilities, and an external committee for vetting proposals for programs to be held at the centre.

- The most ambitious form of a centre would add to this a long range visitors’ program and would allow members of the Canadian theory community to be affiliates, with a program for affiliate visits. It might in addition subsidise postdoctoral fellows, either on site or distributed over Canada, and might even have permanent scientific staff members.

There is widespread support for this idea in principle if the institute is paid for out of new funds, rather than by redistributing funds from other subatomic theory resources (such as individual grants). If a theory institute is created at the expense of individual grant monies, then a detailed cost-benefit analysis must be conducted, which might favour the smaller formats for the institute.

The idea of a centre with a visitors' program, workshops, and longer term programs is particularly appealing to faculty members at remote institutions, who have more difficulty staying abreast of new developments in the field. However, the analogy with Australia is incomplete, because Canada as a whole is not as geographically isolated as Australia; it is much easier and perhaps more natural for Canadian theorists to maintain collaborations and to participate in workshops with individuals and institutions in the United States.

The idea of a postdoctoral program run from a theory institute must also be treated with care. The timing of the application process is quite delicate; it is difficult to have materials prepared much before the postdoc hiring season starts, but the results of the competition for funded postdocs would have to be determined very shortly after that, since the best applicants typically get a job in the first round of postdoc hiring and cannot wait to hear if they will receive a subsidised position. A few subsidised postdoctoral positions will benefit the large research universities but may do so at the expense of smaller institutions, especially if the funds for the postdoc awards arise by diverting from grants in general.

At this time the theory community would favor the formation of an institute if funded mostly or entirely by new funds, and is particularly interested in the prospects of visitors' programs and support for schools, workshops, conferences, and long term programs. The case for an institute paid for by redirecting granting funds is much less clear. A thorough consultation and discussion within the community must take place on other details, such as the location and organization of an institute, before any definite steps are taken.

6 Planning and Budgetary Considerations

6.1 Current funding and main expenses

There are currently 74 subatomic theory researchers receiving discovery grants. The current level of funding is approximately 41,000 CAD per grant, see table 2. These funds are predominantly used to support highly qualified personnel, students and postdocs, with the rest going to cover travel expenses and other research expenses. As the table makes clear, subatomic theory has seen an increase of funding especially over the last 5 years, as a result of the recommendations from the year 2000 long range review. However, the size of this increase should not be exaggerated; as the table shows, much of the increase was needed to offset inflation. In addition, the dominant expenses in subatomic theory are personnel, which must increase with wages, typically 1% to 2% faster than inflation. Taking this into account, funding has not increased that much over the last 10 years.

Year	Number of Grantees	Mean Grant Size	Inflation corrected
1996	71	$ 25 110	$ 30 470
1997	72	$ 24 460	$ 29 130
1998	69	$ 26 709	$ 31 540
1999	68	$ 29 010	$ 33 550
2000	62	$ 30 300	$ 34 180
2001	69	$ 30 760	$ 33 760
2002	72	$ 32 060	$ 34 300
2003	74	$ 34 880	$ 36 590
2004	76	$ 38 180	$ 39 310
2005	74	$ 41 360	$ 41 360

Table 2: Number and mean value of grants in recent years. Grant size covers all grants, including those established before the beginning of the time period. The last column translates grant sizes into constant 2005 dollars. Data from NSERC and Statistics Canada.

Though the current level of funding is adequate, the rising cost of students and postdocs, the expansion expected in the field in the next few years, and the new challenges and opportunities this situation presents, demand careful consideration of the level of funding needed to maintain a successful research programme in the face of changing circumstances.

Specifically, the challenges facing us in the next few years are the following:

- Training of Students: Training of students is one of the strengths of theoretical subatomic physics in Canada. We usually have a large number of students, who are among the best students available. Training in subatomic theory has proven an effective way of providing tools which are useful in many future endeavors, both academic and in industry.

  The training of students in the next few years will present some special challenges, with the focus shifting to more phenomenological studies. We recommend therefore that the students will be able to supplement the basic education they receive in their home institution with travel to national and international schools and conferences. This entails some funds allocated to student travel (most efficiently managed as part of discovery grants), and the funding of national level schools devoted to preparing the students for their future careers. This is most relevant to students from small universities who may otherwise not be exposed at all to some of the themes central to their research.

- Postdoctoral researchers: Most of what we said above about students carries over unchanged to postdoctoral fellows. The central new element when postdocs are considered is our need to provide them with competitive salaries. Canada has some of the best places in the world to pursue theoretical subatomic physics. However, the market for postdocs is very international; there is essentially no travel barrier between the United States and Canada as regards location of postdoctoral study. Therefore, the major obstacle to our attracting the best graduating students in the world is salary. The funding increases of the last 5 years have helped Canada compete a little more effectively with the US, but our salaries still remain substantially below the American average, which is currently in the 40's of thousands of US dollars. Canadian researchers need to consider 45k CAD as a minimum baseline postdoctoral salary to be competitive with the United States, and this amount is likely, like most salaries, to grow faster than the inflation rate in the coming years. The most efficient way to make it possible for Canadian theorists to compete is through increases to discovery grants.

- Travel, conferences, and collaboration: Due to the nature of collaboration in subatomic theory and the geographic isolation of many Canadian theorists already mentioned, it is especially important that Canadian scientists have available the opportunity to travel for collaboration, workshops, and conferences. Two other roles of travel are the dissemination of results and the increase of visibility of the community. At some level, physics research is irrelevant if it is not noticed by the physics community. Publication only does part of the job; presentations at international conferences and seminar talks at remote institutions are also key ways to disseminate new results or ideas.

  It is especially valuable to have sufficient resources to allow students and postdocs to travel, since this broadens their horizons and opens the possibility of collaboration outside of their home institution. Our students and postdocs will not only be better trained if they have travel opportunities, but they are also more likely to find the next job, since we all know that recognition is a key factor in hiring decisions.

  In the next few years this concern will be sharpened, as the centre of high-energy physics will shift geographically to Europe. We expect more of the conferences and collaborative meetings to take place there, a fact which increases our dependence on travel funds.

6.2 What could be done with increased funding?

Most of the central needs outlined above could be met with increased funding for individual discovery grants. This allows flexibility for the researchers, who are in the best position to make informed decisions on how to use their funds to support their research and training of highly qualified personnel. We recommend therefore that in the case of increased funding, most of the increase should be invested in discovery grants.

In addition, this option also allows a substantial increase in support for summer schools, conferences, and workshops. These could for instance be funded through a centre, which could be anything from a granting agency for such money, to an agency with administrative support for conferences, to a venue with administrative support and other centre features already discussed.

How much could be accomplished with additional funding? To see the answer, consider how far the typical discovery grant currently goes. Some minority of theorists have substantial funding sources outside of their discovery grants, but these are fairly limited in subatomic theory; most theorists rely on the discovery grant for essentially all of their research funding. Typically, about 25% of a discovery grant is spent on travel, equipment (such as computers), and expenses (such as network support). For the typical grant, this leaves about 30k for students and postdocs. The cost of a student varies between institutions, but 15K is a typical number. As argued previously, competitive salaries require 45k for a postdoc, even before including payroll overheads. Therefore, a grant covers the pay of 2 students, or 1 student and 1/3 of a postdoc. For researchers at large institutions, this limits the number of students a researcher can take, and means that postdocs are typically shared between faculty members. For researchers at smaller institutions, it means that hiring a postdoc is a substantial challenge, and maintaining a large enough group of students to achieve a "culture" in which more advanced students help in the development of newer students is impossible. This is especially true because researchers at smaller institutions tend to have somewhat below average grants.

Therefore, increased funding could substantially improve the productivity of the theory community and its ability to train HQP. It could particularly help those researchers at smaller institutions. For instance, if grants are doubled over a 10 year period, then after correcting for inflation (2%) and rising payroll costs (1% to 2%), the real increase in spending power would be about 50%. This would allow a typical grant to support a postdoc, 2 students and a shared postdoc, or 3 students. The difference between supporting 1 student and supporting 2 students is more substantial than it sounds, because of the large role that students play in each others' training. Similarly, for institutions without a graduate program, the ability to continuously fund a postdoc at a competitive salary would make a huge difference in a researcher's ability to remain continuously active in their field of study.

6.3 What if funding is held constant?

As in the more optimistic scenario, we recommend that the emphasis will be on keeping the individual grants as healthy as possible. As outlined above, we expect a period of growth and change for the field, following the beginning of the largest experimental effort in a generation. Therefore constant funding is hardly a status-quo situation. This is especially true as we expect that the number of researchers in the field will continue to grow slowly, and as the cost of students and postdocs is rising at least with inflation. Therefore, constant funding actually means a steady erosion of individuals' budgetary positions. In the scenario where funding is held constant, we expect to gradually become less competitive, less attractive to students and postdocs, and less flexible in a fast moving field which requires precisely such flexibility.

Besides trying to maintain the size of individual grants, it will be essential in this case that the granting agencies make sure that they give individuals at isolated institutions sufficient grants to pay for whole numbers of HQP; enough funding to cover 2/3 of a HQP cannot cover anyone. At larger institutions, their costs can be distributed between researchers; at smaller institutions this is not always possible. Therefore grants must either be large enough or distributed correctly over the granting period to allow HQP to be fully funded.

6.4 What if funding is substantially cut?

In the case funding is substantially cut, as much of the remaining amount as possible must be given to individual discovery grants. This scenario will require us to cut down on the number of students we take and will severely restrict the number of theory postdocs hired in Canada (which is unfortunate given the amount of interest in the field). Travel will have to be restricted, which will limit our exposure to new results, and the impact of our work.

7 Conclusions

Subatomic theory and experiment mutually reinforce each other, and neither field can be truly healthy if the other is not. Subatomic theory is also a particularly efficient means for NSERC to carry out one of its main roles, the training of highly qualified personnel–indeed, most of the funding for subatomic theory goes to HQP training. For these reasons, maintaining healthy funding for subatomic theory should remain a priority of the GSC19. This is particularly so with ISAC and LHC, since they will require increased flexibility and resources for the subatomic theory community to take a leading role in understanding the new experimental results and in helping the experimentalists to ask the right experimental questions.

Currently, subatomic theory money goes almost exclusively into individual discovery grants. This should remain true, because the nature of subatomic theory investigation is that it is largely conducted at the individual level, with modest fixed equipment costs. Individual researchers are in the best position to determine how funds can be most efficiently spent. The current system of awarding grants based on individuals rather than projects, with peer review and with amounts determined primarily based on the research track record of the individual, works well for theory and should be continued. It is also important to make sure new theorists receive enough funding to get their research off the ground.

However, there is a need within the community for some funding method to cover workshops, conferences, scientific programs, summer schools, and long term visitors' positions. Currently there is not a good funding mechanism for these interactive opportunities, and it is not generally practical for them to be funded out of individuals' grants. The total amount of money needed for these applications is much smaller than the amount needed for individual grants. Nevertheless, the importance of such meetings and interactive opportunities should not be underestimated. It is a key way for theorists to remain abreast of events in their field, to keep isolated researchers at small institutions involved in research, and to train students and postdocs and open their doors for future positions. It is important for the community to remain flexible, which will be at a premium in the changing environment brought on by new experimenal data from the LHC.

One attractive possibility is a Canadian subatomic theory institute. There is widespread support for such an institute among Canadian subatomic theorists, particularly if its operation comes from fresh funds rather than reallocation of existing subatomic theory funds. If such an institute is created, its mandate should emphasize visitors' programs, conferences, workshops, and schools; there is much less support for postdoctoral programs, which are better handled by individual grants. At this time, the exact size, form, and location of such an institute still needs to be determined. This must be done in a consultative manner, to establish a strong consensus across the community that such an institute is being established in a way which will be of maximal benefit to the broad community.