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Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

Input to Canadian Subatomic Physics Long Range Plan 2022–2037

CINP's process

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Preliminary written briefs: June 5
Virtual Town Hall meeting: June 22–23
Final written briefs: July 10 [33 received, up from 28 in 2015]
Committee met at TRIUMF and virtually Aug 10,11 to draft CINP Brief

We plan to release first draft to community for comment by Sept 1
I will present some draft results of our discussions

Key questions in Nuclear Physics

- Strong international consensus on the most important open questions in Nuclear Physics, as determined by comparison to NSAC and NuPECC reports from 2002–2017.
- By making best use of its established expertise and strengths, and seeking to contribute to the fields of greatest scientific opportunity, the Canadian Nuclear Physics research community has self–selected where to best concentrate its efforts, in alignment with these key questions.

How do quarks and gluons give rise to the properties of strongly interacting particles?

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- We know that hadrons, strongly-interacting composite particles such as protons, neutrons and pions, are made up of quarks and gluons, but we only have partial answers on how quarks are distributed and moving inside.
- Quantum Chromodynamics (QCD), the theory of the strong nuclear interaction between quarks and gluons, describes two regimes – asymptotic freedom and color confinement.
- While the discovery of asymptotic freedom within the context of perturbative QCD was recognized by the 2004 Nobel Prize, we still do not have a complete solution in the confinement regime, where the quark coupling strength is too large to allow the use of perturbative methods.
- **The explanation for the observed properties of the hadrons remains one of the central problems of modern physics, requiring advances in both theory and experiment.**

How do quarks and gluons give rise to the properties of strongly interacting particles?

- Canadian Program:
  - Theory examples:
    - Lattice QCD, Light Front Holographic QCD, Studies of Exotic Hadrons using QCD Sum Rules, Chiral Perturbation Theory
  - Experiment examples:
    - Jefferson Lab
      - GlueX, Meson Form Factors, JLab Eta Factory, SoLID
    - MAMI, DFELL (Compton Scattering)
    - In Longer Term: Electron–Ion Collider

What are the phases of strongly interacting matter, and what roles do they play in the cosmos?

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- Nuclei make up 99.9% of the visible matter in the universe.
- At the highest densities, yet at still rather low temperatures, the quarks making up the nucleons of nuclear matter may form a new state of matter, which is color–superconducting.
- Exotic nuclear matter can also be created by colliding nuclei at relativistic energies.
- In this case, ‘nuclear temperatures’ can reach values that represent a state of matter (the quark–gluon plasma) as it existed during the first moments after the Big Bang.
- **This question has significant bearing on our understanding of astrophysical phenomena such as neutron star structure and the evolution of the early universe.**

- Canadian Program: Relativistic Hydrodynamics

How does the structure of nuclei emerge from nuclear forces?

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- Understanding the strong nuclear force binding protons and neutrons to form the wide variety of complex nuclei has been a long challenge.
- Enormous progress has been made, but it is a central pursuit of current nuclear structure research to reveal the fine details of the strong nuclear force that is responsible for the properties of nuclei and nuclear matter.
- The rare isotopes are breaking the boundaries of our conventional knowledge and reforming our views on how nature organizes the building blocks, protons and neutrons, into a wide variety of complex atomic nuclei.
- Much to our surprise, we are now finding that the well-established nuclear shells that were identified in stable isotopes in the 1950's, disappear in rare isotopes while new ones appear.
- **This brings challenges to our understanding of nature's strong force that is at the heart of existence of all visible matter.**
- **While a few discoveries with light nuclei have opened a new paradigm, much of the rare isotopes remain unexplored.**

How does the structure of nuclei emerge from nuclear forces?

- Canadian Program:
  - Theory examples:
    - Ab-initio No–core shell model with continuum, Valence–space in–medium similarity renormalization group, Nuclear many body theory
  - Experiment examples:
    - Neutron halos in light mass systems
    - Evolution of nuclear shell structure
    - Nuclear collectivity, shape coexistence, shape transitions
      - ISAC and Future ARIEL @ TRIUMF
      - Jefferson Lab (PREX/CREX–II)
      - GSI (Germany)
      - RIBF (RIKEN, Japan)

What is the role of radioactive nuclei in shaping the visible matter?

- August 17, 2017 is noteworthy for the detection of the gravitational wave signal GW170817, followed about 1.7s later by a short γ–ray burst (GRB170817A).
- The event that triggered this gravitational wave emission was identified as a merger of two neutron stars, a scenario that has never been observed before and is connected to the creation of about half of the elements heavier than iron in the so-called "rapid neutron capture (*r*) process".
- **This astrophysical process is deeply connected to the nuclear physics of short-lived neutron-rich nuclei and the Equation of State (EoS) of neutron star matter, and was the prime motivation for the construction of the new generation of radioactive beam facilities worldwide.**
- **Reaction cross section measurements have been limited so far to nuclei close to stability, but this limitation will be overcome in the next decade and help us push our understanding of the creation of the lightest up to the heaviest elements further than anytime before.**

What is the role of radioactive nuclei in shaping the visible matter?

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- Canadian Program:
  - Theory examples:
    - Reverse engineering of *r*–process abundances
    - Neutron star physics and the equation of state
  - Experiment examples:
    - Study of light element creation up to iron peak
    - Nucleosynthesis of heavy elements between iron and uranium
    - ISAC and Future ARIEL @ TRIUMF
      - Jefferson Lab (PREX/CREX–II neutron skin thickness)
      - BRIKEN (Japan)
      - GSI (Germany)

What physics lies beyond the Standard Model?

- The Standard Model (SM) is now half a century old, and in every way has been spectacularly successful.
- Yet, there are extraordinarily compelling reasons to believe that the SM should not be the final answer:
  - It does not explain dark matter nor dark energy
  - It gives no satisfying explanation for the extreme matter-antimatter asymmetry that we observe in our universe
  - It has withstood all efforts to integrate a quantum theory of gravity so far
- In addition, aspects of the SM, while reproducing observations correctly, seem contrived, indicating that we lack deeper understanding.
  - Why are the masses what they are?
  - Why 3 generations of quarks and leptons?
  - Why is only the weak interaction violating parity?
  - Why is this violation maximal, and CP violation seems unnaturally small?

What physics lies beyond the Standard Model?

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- Nuclear physics, and closely associated experiments in atomic and molecular (AMO) physics, at the low-energy, precision, frontier, have played an important role all along in trying to answer these questions, complementary to high energy techniques.
- Advantages of this community are the diversity of efforts, nimble response to the changing landscape, relatively modest budgets, and diverse HQP training.
- Increasingly, a connection is forming to the emerging field of “quantum sensing”, or more broadly “quantum technology”, promising major gains in experimental sensitivity.
- **Canada continues to punch above its weight in this domain, with numerous efforts at two world–class domestic facilities, TRIUMF, and SNOLab, as well as abroad, for example at JLab and CERN, covering most aspects of searches for physics beyond the SM.**

Executive Summary

- The Recommendations to Follow are needed for the Canadian Nuclear Physics community to make optimal progress in pursuit of the Key Questions
- **Please keep in mind these are our most recent DRAFT**
- **The full set of Recommendations will be released in our first draft of the CINP Brief on September 1**

Recommendation 1

- **Enhance Nuclear Theory Support**
- Advancement of nuclear physics is strongly dependent on interplay between theory and experiment
- Some examples:
  - Indirect searches for new physics at TeV scale
  - Nuclear corrections are largest systematic uncertainty in neutrino oscillation data
  - Ab–initio and phenomenological modeling identifies promising new directions for experimental work
- The key to successful collaboration is close coordination and rapid theory response to needs of experimental programs
- **Recommend increased support at a level to allow travel and support postdocs, graduate students**

Recommendation 2

- **Fund the additional HQP needed to capitalize on new or recently–upgraded facilities**
- Substantive progress towards the resolution of the key questions in nuclear physics requires HQP
- Despite this clear need, 2017–2021 LRP indicated broad *“capacity to train about 80% more students, if additional funding were available”*
- Recent strategic investments have enabled the development of several major new experimental facilities with very high scientific merit, and Canadians are well–placed to take advantage of these opportunities
- **It is essential that a corresponding increase be made in the NSERC SAP envelope to support the research teams that will drive the scientific output from these new facilities**

Recommendation 3

- **Leverage the scientific opportunities enabled by the completion of ARIEL**
- ARIEL is TRIUMF's flagship project, conceived to ensure Canada's leadership role in rare isotope science
- During the period covered by the LRP, ARIEL will begin to deliver science in a phased approach, allowing a large number of high priority measurements to more quickly move ahead
- **To fully leverage these opportunities, Government of Canada support for TRIUMF to allow for operational support necessary to fully exploit the science opportunities of ARIEL (9000 hr of RIB/yr) is essential**
- **Strategic operating grant investments by NSERC to ensure the dissemination of results in a timely fashion is also critical to maximize the scientific output**

Recommendation 4

- **Position Canada for Leadership in Future International Nuclear Physics Research**
- To advance our understanding of the Key Questions of Nuclear Physics, it is understood that Canadians must be leading participants in the development of major international projects
- The Electron–Ion Collider (EIC) is a major international facility on the future horizon, which will uniquely address profound question about nucleons (neutrons and protons) and how they are assembled to form the nuclei of atoms
- Canadians are involved in the planning of the EIC program, and are represented on the EIC User's Group Steering Committee
- **A substantial involvement in the EIC project will confirm Canada's leadership role in scientific research and development**

Recommendation 5

- **Grow the Nuclear Physics Community**
- Over the 15 years of the LRP, there will be a large renewal of the scientific researcher ranks of our field
- Substantial scientific opportunities, such as ARIEL and EIC, make the case for an expansion of investment in Nuclear Physics research in universities across Canada
- Historically, Bridge Faculty Positions have proven to be an effective way to strategically grow research capacity in highly promising fields within Canadian universities
- **We encourage our community to seek innovative sources of funds for such positions, so that the substantial scientific opportunities we see in the next 15 years can be best taken advantage of**

Recommendation 6

- **Foster a funding environment which enables Canadian Researchers to lead in science and discovery**

a) Sufficient and versatile funding opportunities for both capital equipment and operational funding is essential. The interplay between NSERC, CFI and the new Computing Agency needs to be strengthened, so that capital, operating fund and high performance computing resource decisions are coordinated and streamlined

b) NSERC and TRIUMF should continue to provide technical resources and capabilities for construction of experiments

c) Ongoing investments in detector and accelerator R&D are needed

Tentative plans for your input

- **First draft released: September 1**
- Written comments due: September 21
- Second draft released: October 12
- **Second Virtual Town Hall to gather further input and consensus: October 26**
- Third draft released: November 6
- Final comments due: November 16
- **Report submitted to LRPC: December 1**