REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

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Donald Geesaman (Chair)   Argonne National Laboratory

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Abhay Deshpande   Stony Brook University

Frederic Fahey   Boston Children's Hospital

John Hardy   Texas A&M University

Karsten Heeger   Yale University

David Hobart   Chair, American Chemical Society Division
of Nuclear Chemistry and Technology

Suzanne Lapi   Washington University

Jamie Nagle   University of Colorado

Filomena Nunes   Michigan State University

Erich Ormand   Lawrence Livermore National Laboratory

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Jurgen Schukraft   European Organization for Nuclear Research

Kate Scholberg   Duke University

Matthew Shepherd   Indiana University

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Michael Wiescher   Notre Dame University

John Wilkerson   University of North Carolina, Chair of American
Physical Society Division of Nuclear Physics

Preface

Explorers, inventors, and scientists are constantly striving to reach to the horizon and beyond. Wilbur and Orville Wright made flight in a powered, heavier-than-air machine a reality in the winds of Kitty Hawk, North Carolina. Today, nuclear science is at a stepping-off point in reaching for the horizon. The exploration of nuclear science has been guided by a series of long range plans prepared by the Nuclear Science Advisory Committee (NSAC) at the request of the Department of Energy (DOE) Office of Science and the National Science Foundation (NSF) Directorate of Mathematical and Physical Sciences. In a letter dated 23 April 2014, NSAC was again charged to conduct a new study of the opportunities and priorities for United States nuclear physics research and to recommend a long range plan that will provide a framework for the coordinated advancement of the Nation's nuclear science program over the next decade.

While the charge was given to NSAC, the entire community of nuclear scientists in the U.S. actively contributed to developing the plan in a series of town meetings and white papers under the leadership of the American Physical Society Division of Nuclear Physics. Ideas and goals, new and old, were examined, and community priorities were established. A long range plan working group composed of 58 members from across the field and with international participation gathered in Kitty Hawk in April 2015 to converge on the long range plan.

The last long range plan in 2007 was created at a time when there was a commitment to double the funding for physical science research over the next decade. It followed the 2000–2007 time period where no new major construction had occurred, and the focus was on operating the then-new facilities we had built. The 2007 plan's recommendations focused on major new initiatives, and these could be accommodated with this doubling budget assumption. In the past seven years, this increasing budget scenario has not been realized, and, in 2013, NSAC responded to a charge to advise how to implement the 2007 plan under flat budget scenarios.

The charge for the 2015 Long Range Plan asked what resources and funding levels would be required to maintain a world-leadership position in nuclear physics research and what the impacts and priorities should be if the funding available provides for a constant level of effort. The 2015 plan will involve hard choices if we are to go forward with constrained budget scenarios. Our vision was to create a plan that would address the important scientific questions while requiring only modest growth in the nuclear science budgets of DOE and NSF. Realizing this vision is possible with careful staging of new initiatives while fully exploiting the opportunities of our past investments and taking into account complementary international initiatives.

Inspired by the symbolism of the Wright brothers' great leap forward in the winds of Kitty Hawk, the new plan, *Reaching for the Horizon*, offers the promise of great leaps forward in our understanding of nuclear science and new opportunities for nuclear science to serve society. Following its guidance, the United States will continue as a world leader in nuclear science.

1. Summary and Recommendations

From the hot dense soup of quarks and gluons in the first microseconds after the Big Bang, through the formation of protons and neutrons beginning the evolution of the chemical elements, to the awesome power of nuclear fission, bringing both strength and complicated nonproliferation issues to our national security, the physics of nuclei is fundamental to our understanding of the universe and, at the same time, intertwined in the fabric of our lives. Nuclear physicists and chemists are creating totally new elements in the laboratory and producing isotopes of elements that, hitherto, have only existed in stellar explosions or in the mergers of neutron stars. They develop new tools like accelerators and detectors that find broad applications in industry, medicine, and national security. The United States, with the support of the National Science Foundation (NSF) and the Department of Energy (DOE), has world-leading programs in nuclear science, from forefront basic research to the development of important new applications for society.

Since 1979, progress in nuclear science has been guided by a series of six Nuclear Science Advisory Committees' (NSAC) long range plans, the last one created in 2007. In April 2014, NSAC was charged by the DOE Office of Science and the NSF Directorate of Mathematical and Physical Sciences to conduct a new study of the opportunities and priorities for United States nuclear physics research and to recommend a long range plan that will provide a framework for the coordinated advancement of the Nation's nuclear science program over the next decade. The plan should indicate what resources and funding levels would be required to maintain a world-leadership position in nuclear physics research and what the impacts and priorities should be if the funding available provides for constant level of effort from the fiscal year (FY) 2015 President's Budget Request into the out-years. The full text of the charge is given in Appendix A.1. The Isotope Program of the DOE Office of Nuclear Physics is explicitly excluded from the charge, as it is the subject of a separate charge to NSAC.

NSAC created a Long Range Plan working group of 58 members (Appendix A.2), including scientists from Europe and Canada and with international observers representing associations of nuclear scientists from Europe and Asia. In a nine-month-long process, the Division of Nuclear Physics of the American Physical Society organized broad input for the working group, including several town meetings (listed in Appendix A.3) and white papers (available at https://www.phy.anl. gov/nsac-lrp/). The working group held two meetings, an organizational meeting in November 2014, and a resolution meeting (see Appendix A.4) in April 2015, to establish recommendations and priorities. It is well recognized that resources are always limited, and hard choices have been made concerning parts of the program that could not go forward in a realistic budget scenario. For example, the 2013 NSAC report *Implementing the 2007 Long Range Plan* responded to a more constrained budget picture than was originally expected. The resulting focused plan has been widely supported by the community, the Administration, and Congress. This 2015 Long Range Plan also involves hard choices to go forward with constrained budget scenarios.

THE SCIENCE QUESTIONS

Nuclear science is a broad and diverse subject. The National Research Council Committee on the Assessment of and Outlook for Nuclear Physics 2013 report, *Nuclear Physics, Exploring the Heart of Matter*, (NP2010 Committee) framed the overarching questions "that are central to the field as a whole, that reach out to other areas of science, and that together animate nuclear physics today:

1. How did visible matter come into being and how does it evolve?
2. How does subatomic matter organize itself and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?"

The progress in nuclear science since the last long range plan in 2007, as well as new questions that now demand to be answered, will be identified in the science sections of this report. The 2007 plan has served the community and the funding agencies extremely well as a blueprint for the future. Indeed, given the size and the decade-long time scales for major construction projects,

in some cases, we are only now poised to reap the benefits of these initiatives. In other cases, anticipated upgrades were achieved at a small fraction of the cost estimated in 2007, and we are harvesting the benefits earlier than expected. All of our current four national user facilities, the Continuous Electron Beam Accelerator Facility (CEBAF), the Relativistic Heavy Ion Collider (RHIC), the Argonne Tandem Linac Accelerator System (ATLAS), and the NSF-supported National Superconducting Cyclotron Laboratory (NSCL), were significantly upgraded in capability during this period. A fifth national user facility, the DOE-supported Holifield Radioactive Ion Beam Facility, was closed down. Care was always taken to leverage U.S. investments in an international context while maintaining a world-leadership position.

Here are the recommendations of the 2015 Long Range Plan.

RECOMMENDATION I
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*
- *Expeditiously completing the Facility for Rare Isotope Beams (FRIB) construction is essential. Initiating its scientific program will revolutionize our understanding of nuclei and their role in the cosmos.*
- *The targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model must be sustained.*
- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

Realizing world-leading nuclear science also requires robust support of experimental and theoretical research at universities and national laboratories and operating our two low-energy national user facilities—ATLAS and NSCL—each with their unique capabilities and scientific instrumentation.

The ordering of these four bullets follows the priority ordering of the 2007 plan.

RECOMMENDATION II
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.

RECOMMENDATION III
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon

fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

The vision of an EIC was already a powerful one in the 2007 Long Range Plan. The case is made even more compelling by recent discoveries. This facility can lead to the convergence of the present world-leading QCD programs at CEBAF and RHIC in a single facility. This vision for the future was expressed in the 2013 NSAC report on the implementation of the 2007 Long Range Plan with the field growing towards two major facilities, one to study the quarks and gluons in strongly interacting matter and a second, FRIB, primarily to study nuclei in their many forms. Realizing the EIC will keep the U.S. on the cutting edge of nuclear and accelerator science.

RECOMMENDATION IV

We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

Innovative research and initiatives in instrumentation, computation, and theory play a major role in U.S. leadership in nuclear science and are crucial to capitalize on recent investments. The NSF competitive instrumentation funding mechanisms, such as the Major Research Instrumentation (MRI) program and the Mathematical & Physical Sciences mid-scale research initiative, are essential to enable university researchers to respond nimbly to opportunities for scientific discovery. Similarly, DOE-supported research and development (R&D) and Major Items of Equipment (MIE) at universities and national laboratories are vital to maximize the potential for discovery as opportunities emerge.

These NSF funding mechanisms are an essential component to ensure that NSF-supported scientists have the resources to lead significant initiatives. These programs are competitive across all fields, and an increase in the funds available in these funding mechanisms would benefit all of science, not just nuclear physics.

With both funding agencies, small- and mid-scale projects are important elements in increasing the agility

of the field to react to new ideas and technological advances. The NP2010 Committee report also made a recommendation addressing this need. With the implementation of projects, there must be a commitment to increase research funding to support the scientists and students who will build and operate these projects and achieve the science goals. Close collaborations between universities and national laboratories allow nuclear science to reap the benefits of large investments while training the next generation of nuclear scientists to meet societal needs.

NSAC is asked to identify scientific opportunities and a level of resources necessary to achieve these. So, except for the largest-scale facilities, projects named in this report are given as examples to carry out the science. The funding agencies have well-established procedures to evaluate the scientific value and the cost and technical effectiveness of individual projects. There is a long-standing basis of trust that if NSAC identifies the opportunities, the agencies will do their best to address these, even under the constraints of budget challenges.

INITIATIVES

A number of specific initiatives are presented in the body of this report. Two initiatives that support the recommendations made above and that will have significant impact on the field of nuclear science are highlighted here.

A: Theory Initiative

Advances in theory underpin the goal that we truly understand how nuclei and strongly interacting matter in all its forms behave and can predict their behavior in new settings.

To meet the challenges and realize the full scientific potential of current and future experiments, we require new investments in theoretical and computational nuclear physics.

- *We recommend new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing. These investments include a timely enhancement of the nuclear physics contribution to the Scientific Discovery through Advanced Computing program and complementary efforts as well as the deployment of the necessary capacity computing.*

1. Summary and Recommendations

- *We recommend the establishment of a national FRIB theory alliance. This alliance will enhance the field through the national FRIB theory fellow program and tenure-track bridge positions at universities and national laboratories across the U.S.*
- *We recommend the expansion of the successful Topical Collaborations initiative to a steady-state level of five Topical Collaborations, each selected by a competitive peer-review process.*

B: Initiative for Detector and Accelerator Research and Development
U.S. leadership in nuclear physics requires tools and techniques that are state-of-the-art or beyond. Targeted detector and accelerator R&D for the search for neutrinoless double beta decay and for the EIC is critical to ensure that these exciting scientific opportunities can be fully realized.

- *We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC.*

WORKFORCE, EDUCATION, AND OUTREACH

A workforce trained in cutting-edge nuclear science is a vital resource for the Nation. Exciting research is intimately tied with attracting talented graduate students to any science, including nuclear science. Workforce surveys show that the total number of Ph.D. graduates in nuclear science has been constant for the past decade, which is consistent with the U.S. continuing to attract the best and brightest students for graduate education and research, both from the U.S. and abroad. However, compared to the patterns 10 years ago, a higher percentage of nuclear physics faculty at universities and national laboratories and of faculty recipients of prestigious early career awards received their Ph.D.s from universities outside the U.S. There is a continuing vital need to enhance the development of a talented U.S. workforce by increasing the participation of U.S. students in the opportunities in basic and applied nuclear science. To increase the number of U.S. students prepared for successful graduate studies and research in nuclear science requires opportunities for undergraduates to be engaged in forefront nuclear science research and studies. Graduate students are also inspired by highly visible postdoctoral positions to which they can aspire.

Our Nation needs a highly trained workforce in nuclear science to pursue research, develop technology, and ensure national security. Meeting this need relies critically on recruiting and educating early career scientists.

We recommend that the NSF and DOE take the following steps.

- *Enhance programs, such as the NSF-supported Research Experiences for Undergraduates (REU) program, the DOE-supported Science Undergraduate Laboratory Internships (SULI), and the DOE-supported Summer School in Nuclear and Radiochemistry, that introduce undergraduate students to career opportunities in nuclear science.*
- *Support educational initiatives and advanced summer schools, such as the National Nuclear Physics Summer School, designed to enhance graduate student and postdoctoral instruction.*
- *Support the creation of a prestigious fellowship program designed to enhance the visibility of outstanding postdoctoral researchers across the field of nuclear science.*

Research in theory, experiment, and computation as well as instrumentation initiatives from university groups and laboratories provide a unique education and training environment that must be nurtured.

RESOURCES

The working group carefully considered the budgetary implications of its recommendations. The construction funding of FRIB will be winding down in FY 2020–2021. It is expected that project selection for a ton-scale neutrinoless double beta decay experiment will occur in a few years, and then this project will commence. An EIC is envisioned to start construction after FRIB construction is completed and to be operational by the end of the 2020s. With this sequencing, an effective and efficient program in nuclear science can be accomplished with a DOE nuclear science budget that increases by 1.6% in spending power above cost of living per year for the ten years of this plan. This is consistent with the scenario advocated in the 2013 NSAC report, *Implementing the 2007 Long Range Plan*. Under this constraint, some important science would rely on international efforts, and a number of promising avenues cannot be pursued, but the U.S. program will be strong, vital, and world leading. Under a budget that represents constant effort at the

level of the appropriated FY 2015 budget, the decisions become more difficult. Promising opportunities will be lost. The technology choices for some of the major projects may become driven more by cost rather than by optimizing the science reach. There would be less scope to follow up new discoveries at FRIB, CEBAF, and RHIC. The EIC must begin more slowly. U.S. leadership would be maintained in some areas but would be given up in others. Nonetheless, a constant effort budget can fund a sustainable program for nuclear science, one of the elements of the charge.

For the NSF, it is anticipated that the operations budget of the NSCL will terminate once FRIB operations commence. Before the transition, NSCL will remain the premier national user facility for rare isotope research in the U.S., with unique rare isotope reacceleration capabilities following fast beam fragmentation. We project a slightly increasing total NSF nuclear physics funding from FY 2015 as new instrumentation and mid-scale projects led by NSF-supported scientists emerge to address the recommendations above.

The balance of the report begins with presenting the frontiers and accomplishments in each of the sub-disciplines of nuclear science: understanding nuclei in terms of the fundamental quarks and gluons; the structure and reactions of nuclei; the intimate relation between nuclear physics and astrophysics; and unique nuclear science searches for the new Standard Model of particles and interactions. The following four chapters point out cross-cutting issues in nuclear theory, place the domestic facilities and tools that enable much of this research in an international context, discuss issues of the scientific workforce and education, and highlight the broader impacts of nuclear science on other sciences and society. The plan concludes with a discussion of the budgets required to continue U.S. world leadership in nuclear science.

2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

It was just under a hundred years ago that Lord Rutherford uncovered the existence of the proton as one of the basic building blocks of the atomic nucleus. The discovery of the other building block, the neutron, came more than a decade later. By the middle of the twentieth century, many features of nuclear physics were well established, including the strong force that binds protons and neutrons within an atomic nucleus. A multitude of other strongly interacting particles, named hadrons, had also been discovered. But, even as applications of nuclear physics were developed, a fundamental understanding of the underlying laws of physics was missing. This ultimately changed when quantum chromodynamics (QCD) was established as the fundamental theory governing nuclear matter and all hadrons.

QCD holds that protons, neutrons, and all other hadrons are made from quarks, their antimatter siblings (antiquarks), and particles called gluons that carry the force binding quarks to each other. Protons and neutrons can be thought of as containing three so-called valence quarks, immersed in a shimmering cloud of quarks, antiquarks, and gluons, all continually winking into and out of existence according to the laws of quantum mechanics. Similarly, quarks and gluons are the building blocks of all hadrons. No single quark or gluon, however, can be observed in isolation. One says that they are *confined* within a hadron. Confinement is a hard pill to swallow when our experience tells us that we should be able to disassemble an object that has composite parts. Confinement means that any process by which one rips a quark out of a proton or neutron makes new hadrons, without ever isolating a single quark

Gluons carry the force between quarks in much the same way that electromagnetic forces are carried by the photon. There is, however, a hugely important difference. Photons interact with objects that have charge but do not carry charge themselves. This means that photons do not interact with each other. In contrast, gluons interact with objects that carry color charge, and they also carry color charge themselves. Thus, gluons can interact among themselves and even spawn additional gluons, a phenomenon that has bizarre consequences. For example, the force between two quarks becomes *small* when they move close together but grows *large* when they move apart, the opposite of the case in electromagnetism!

All of these unusual features of QCD result in a structure for the proton and neutron that is quite remarkable. It turns out that the intrinsic mass of the three valence quarks in the nucleon comprises only a small fraction of the nucleon's total mass. The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. Since protons and neutrons account for nearly all the mass of atoms, nearly all of the mass of the visible matter in the universe is due to these seemingly exotic QCD effects. And while these general features of nuclear matter are well established, a detailed understanding of how this all comes about from QCD is only now emerging.

The fundamental laws of QCD are elegantly concise; however, understanding the structural complexity of protons and neutrons in terms of quarks governed by those laws is one of the most important challenges facing physics today, a challenge that motivates the newest generation of experimental facilities, supercomputers, and nuclear scientists. There has been impressive progress. Scientists have taken important first steps toward understanding how nuclei are built from quarks. Recent advances in calculational power now allow for precise calculations of the masses of hadrons (Sidebar 2.1). These same calculations predict that because gluons interact with gluons there should be as-yet undiscovered hadrons in which gluons play as central a role as the valence quarks. A new experimental search for these novel exotic particles, using cutting-edge instrumentation now being commissioned, will soon be underway. Another outstanding challenge is the understanding of how protons get their spin: does it come entirely from the intrinsic spin of quarks and gluons? Very recently, we have learned that the spins of the gluons do make an important contribution. But is orbital motion of constituents within the proton important? Do quarks, antiquarks, and gluons all swirl in the same direction? Here, too, new measurements and new calculations are much anticipated.

2. Quantum Chromodynamics: The Fundamental Description of the Heart of Visible Matter

While it is impossible to observe a single quark in isolation, that does not mean that quarks are necessarily always confined. A spectacular example of unconfined quarks can be found in the behavior of matter at temperatures above three trillion degrees Fahrenheit, the matter that filled the universe in the first microseconds after it came into existence in the Big Bang. The enormously large thermal energy in these conditions makes hadrons literally melt and form quark-gluon plasma (QGP). Quarks can roam throughout a large droplet of QGP; within it, they are not confined into hadrons. In fact, the protons, neutrons, and other hadrons that condensed out of QGP as the universe cooled below QGP temperatures were the first complex structures ever to form. With the highest energy accelerators in the world, scientists are today recreating tiny droplets of the hot QGP matter that filled the universe before hadrons existed and studying their properties in the laboratory. Although the quarks in QGP are not confined to individual hadrons, they are also far from isolated: recreating QGP in the laboratory yielded the surprising discovery that QGP is a nearly perfect liquid, that is, a fluid whose viscosity is about as low as is theoretically possible. How quarks and gluons conspire to form such a liquid is not yet understood. Unraveling how the perfect fluid works, how it emerges from the simple underlying laws of QCD, requires probing QGP with "microscopes" with varying resolving power and changing its makeup by doping it with more quarks than antiquarks.

We are still far from a comprehensive and quantitative understanding of how the many properties of protons and nuclei arise from quarks and gluons and their interactions or of how these interactions conspire to create the hottest, and most "liquid," liquid ever seen in the universe. This Long Range Plan lays out the path by which U.S. nuclear science can lead the worldwide quest to unravel these mysteries and gain new fundamental understanding of QCD in all its manifestations. The investigative tools for this quest are particle accelerators, including two newly upgraded facilities: CEBAF at the Thomas Jefferson National Accelerator Facility (TJNAF or JLab), whose energy doubling upgrade is just being completed; and RHIC at Brookhaven National Laboratory (BNL), recently upgraded to increase its beam intensity by a factor of ten. In addition to searching for novel exotic particles, CEBAF will map out the valence quark structure of protons and neutrons in unprecedented

detail, creating exquisite images of how the quarks in them are distributed in space and how they are moving. RHIC will use very heavy or energetic quarks to probe the properties of liquid QGP with varying resolving power and will map out how the transition between liquid QGP and ordinary matter changes with doping, searching for a distinctive critical point in the phase diagram of QCD. Accelerators at Fermilab are also important as are international endeavors such as the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN).

That said, today's tools will leave fundamental questions related to the role of gluons within protons, neutrons, and nuclei unanswered. As scientists examine protons and neutrons more and more closely, the importance of the role of gluons in their structure is becoming increasingly apparent. Furthermore, understanding how QGP forms when two nuclei collide is thought to be connected to understanding how it is that many gluons within a single nucleus can act in concert like a classical wave rather than as many individual particles. A complete understanding of how protons and nuclei are built and of how QGP forms will require a powerful new experimental tool, a polarized EIC. The EIC will make it possible to resolve the gluon structure of the proton and of nuclei with the same precision with which CEBAF will map their quark structure. The EIC will perform precise measurements to complete our picture of how the proton's spin is generated by quarks and gluons. And it will explore how the interactions among gluons themselves serve to prevent the numerous gluons within fast-moving nuclei from clustering into arbitrarily dense states. Ultimately, the EIC will provide the data that will help us understand the mass and other fundamental properties of protons and neutrons from first principles. Together with anticipated advances in our ability to solve the equations of QCD, these experimental explorations will help us explain how the properties of nuclear matter can arise from complex solutions to simple equations. The EIC will take a critical step in the study of QCD by opening a new window into the crucial role played by gluons in all matter.

In the chapter ahead, we examine the many achievements since the 2007 Long Range Plan, describe what can be accomplished in the future with existing facilities, and look ahead to the discovery potential of an EIC.

2.1 QCD and the Structure of Hadrons and Nuclei

THE QUARK STRUCTURE OF HADRONS

Understanding the structure of hadrons in terms of QCD's quarks and gluons is one of the central goals of modern nuclear physics. This endeavor is profoundly difficult, however, since we cannot simply think of hadrons as being solely composed of their valence quarks but must fold in the roles played by both the gluons that bind quarks and the quark-antiquark pairs associated with quantum fluctuations.

Despite considerable challenges, however, through both theoretical and experimental progress, physicists have begun to tease out the structure of hadrons. Facilities such as CEBAF and RHIC have provided tools of unprecedented capability. Theoretical techniques such as lattice QCD and increasingly realistic models are providing new and deeper understanding of experimental observations. Our knowledge of the spatial distribution and the motion of the quarks has become more detailed, and we are now starting to unfold the dynamics that give hadrons their basic properties. This quest is still at an early stage, but the progress that has been made since the 2007 Long Range Plan is considerable, and the next decade promises to be one of increasingly sophisticated understanding and discovery.

A New Era in the Theory of Hadron Structure

While quantum mechanics made it possible to compute the structure of atoms, using QCD to compute the structure of hadrons has long been an elusive goal. That, however, is rapidly changing. It can truly be stated that we are entering a new era in our theoretical understanding of hadron structure. Lattice QCD (see Sidebar 2.1) can now be used to compute certain properties of hadrons, and even light nuclei, from first principles with a precision that is well quantified and only limited by available computational resources.

Furthermore, effective field theories and increasingly realistic models are describing hadron structure in a manner that advances our understanding of the underlying physics. These include both models in which quarks are treated as constituent degrees of freedom with effective masses and QCD-inspired field theories in which the effective mass of the quark is dynamically generated. Much progress has been made since the

2007 LRP, and the promise of future breakthroughs in understanding is truly exciting.

The Size, Shape and Makeup of Hadrons
Form Factors—The Closest Thing We Have to a Snapshot

With such theoretical predictions in hand, one can essentially construct a snapshot of a particle and compare to experiment. These properties can be experimentally determined by extracting "form factors" from the elastic scattering of electrons, scattering in which the object being struck recoils but remains intact. The resolution of the image, or **resolving power**, is determined by the momentum that is transferred to the object—the higher the momentum transfer, the higher the resolution. From the first measurement of the size of the proton by Hofstadter in the 1950s, to some of the most important discoveries to emerge from JLab, form factors have played a critical role in our evolving understanding of hadron structure.

The Strange-Quark Form Factors of the Nucleon

While the three valence quarks of the proton are two up (u) quarks and one down (d) quark, there are also quark-antiquark pairs—termed sea quarks—due to quantum fluctuations. For many years, there were both theoretical and experimental reasons to believe that the strange sea quarks might play a significant role in the nucleon's structure; a better understanding of the role of strange quarks became an important priority.

Two notable accomplishments presented in the 2007 LRP were constraints on the contributions of strange quarks to the electric and magnetic properties of the proton obtained through the study of parity violation in electron scattering. In such measurements, polarized electrons are scattered from unpolarized targets, and one looks for tiny changes in the scattering of electrons when the beam spin is reversed. Such changes represent a violation of the parity (or "mirror") symmetry and are due to the weak force, the only force that behaves differently in a "looking glass" world. These experiments measure the weak-force equivalent of the charge and magnetism distributions, which can be combined with precision electromagnetic data to disentangle the strange-quark contributions. The time period since the 2007 LRP has seen the successful conclusion of this experimental program, which conclusively shows that strange-quark contributions to nucleon form factors are consistent with zero and not more than a few percent.

Parity-violating electron scattering is an important part of JLab's program and will continue to be so in the future. Examples include the Qweak experiment, which measured the "weak charge" of the proton, and PREX, which measured the radius of the neutron distribution in lead. Future proposed experiments include PREX-II, CREX, MOLLER, and a program utilizing the SoLID detector. These experiments are covered in Chapters 3–5.

Flavor Separated Form Factors of the Nucleon
At the time of the 2007 LRP, the elastic form factors of the proton were known to much higher momentum transfer than was the case for the neutron. A lingering discrepancy also remained between the determinations of the proton form factors between two experimental methods, ascribed to the probability that two photons rather than one were exchanged in the electron scattering process. The latter hypothesis has been the topic of experiments comparing electron and positron scattering and appears correct. Furthermore, the range over which the neutron's form factors are known has now more than doubled. This, together with the aforementioned constraints on strange-quark form factors, has made it possible to extract the form factors associated with u and d quarks individually by combining data from both the proton and the neutron.

The results are illustrated in Figure 2.1. Surprisingly, the u- and d-quark contributions differ with increasing Q^2 or resolving power. Several theoretical interpretations of their behavior seem to suggest the presence of *diquark-like structures* within the nucleon, structures in which two of the quarks in the nucleon are much closer to one another than they are to the third quark. Such diquark-like structures have long been hinted at by baryon spectroscopy (see the "Hadron Spectroscopy" section), so it is exciting to see possible evidence for them in a very different context.

One of the important goals of JLab's 12-GeV upgrade is to push our knowledge of the elastic nucleon form factors into new territory. For the proton, the range of momentum transfer will be significantly increased, and the precision will be dramatically improved. For the neutron, the range of momentum transfer will be nearly tripled. The "Super Bigbite Spectrometer" (SBS) under construction in JLab's Hall A will be critical here. Given the important discoveries that have already emerged from form-factor measurements at JLab, the discovery potential of these new measurements is considerable.
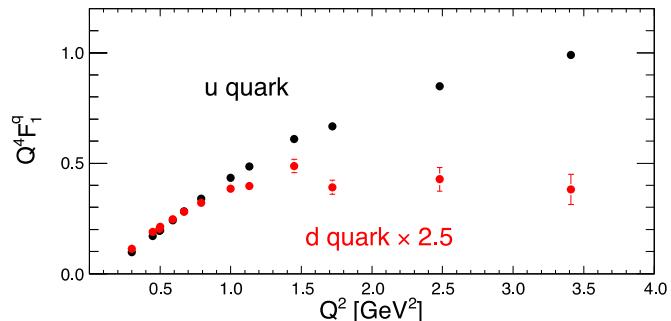
Figure 2.1: *The u- and d-quark contributions to the nucleon form factors and their surprising difference. The extraction of these quantities was made possible by measuring the neutron form factors to high values of momentum transfer. The range will be tripled with JLab's 12-GeV Upgrade.*

A Puzzle Surrounding the Size of the Proton
Physicists around the world are seeking a solution to a puzzle concerning the charge radius of the proton. Recent results from precise atomic spectroscopy using muonic hydrogen found the radius to be seven standard deviations smaller than the previous accepted value extracted from a combination of form-factor measurements using electron scattering and atomic spectroscopy using conventional hydrogen. Theorists are exploring ways to explain this discrepancy, including the possibility that it is due to physics beyond the Standard Model. New generations of precise experiments are planned to address the mystery, including the PRad experiment at JLab (electron scattering at very small angles) and the muon-scattering MUSE experiment at the Paul Scherrer Institut (PSI).

The Charged Pion Form Factor
The pion plays a unique role in nature. It is the lightest quark system, with a single valence quark and a single valence antiquark. It is also the particle responsible for the long range character of the strong interaction that binds the atomic nucleus together. Physicists believe that the underlying rules governing the strong interaction are left-right—that is, chirally—symmetric. If this were completely true, the pion would have no mass. But the chiral symmetry of massless QCD is broken dynamically by quark-gluon interactions and explicitly by inclusion of light quark masses, giving the pion mass. Thus, the pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.

With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12-GeV Upgrade. It will be studied using a new instrument, the "Super-High Momentum Spectrometer"

Sidebar 2.1: Solving the Structure of Hadrons and Light Nuclei with Lattice QCD

The building blocks of nuclei, protons and neutrons, are comprised of quarks and gluons. Quantum chromodynamics (QCD), the theory describing the interactions of quarks and gluons, is well known, and its equations can be written down in an elegant manner. QCD has had tremendous successes, for example, it allows direct comparisons of its predictions with experiments at high energies, where "deep inelastic scattering experiments" have beautifully revealed the quark and gluon substructure of protons, neutrons, and nuclei. However, precise descriptions of many low-energy properties of even the simplest systems, such as protons and neutrons, have remained elusive. A top priority of nuclear physics has been to develop first-principles predictive capabilities for low-energy processes described by QCD.
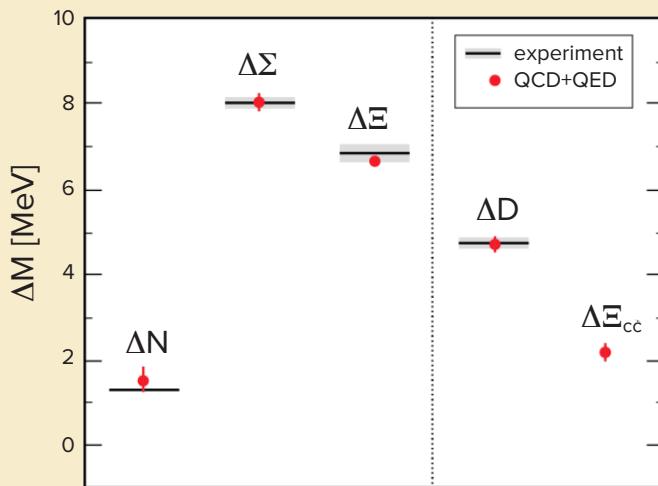
Figure 1: Shown are the mass differences between "isospin pairs" of baryons, such as a proton and a neutron (ΔN), and other unstable isospin pairs. Experimental values (gray bands) are compared with LQCD, including electromagnetic effects (red points). It is remarkable that differences in these baryon masses at the level of one part in a thousand can now be precisely calculated from first principles.

To achieve predictive capability, a numerical technique to perform QCD calculations has been developed: lattice QCD (LQCD). LQCD combines breathtaking advances in high-performance computing, innovative algorithm and software development, and conceptual breakthroughs in nuclear theory. In LQCD, space and time are described as points on a grid. Quarks and gluons are also defined on this grid, and their interactions with one another can

be calculated numerically. Next, a widely used set of approaches to computer simulations, known as Monte Carlo methods, is employed. Basically, a large number of computer-generated configurations of the quantum fields are created and analyzed, and out of this process the true behavior of the quarks and gluons emerges. In principle, any level of accuracy can be obtained, limited only by computational resources and available work force.

The progress in LQCD calculations since the 2007 Long Range Plan has been dramatic. For the first time, calculations are being performed using the physical quark masses rather than the artificially increased masses that were needed previously. The effects of electromagnetism are being included as well. In Figure 1, the impressive agreement of calculated and measured mass differences between isospin partners amongst the hadrons confirms that QCD provides an accurate description of strongly interacting matter.

Underscoring this huge progress, LQCD plays an essential role in guiding experimental work. GlueX at JLab, one of the flagship experiments of the 12-GeV Upgrade, is designed to search for exotic particles where the "glue" is in an energetically excited state. Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

Tremendous progress has been made in the calculation of hadron-hadron scattering probabilities. Phase shifts and mixings describing the low-energy scattering behavior have been successfully calculated for elastic pion-pion scattering, including mapping out the shape of the rho resonance, and, recently, for multi-channel scattering. The mixing is highlighted in the extraction of resonance information in pion-kaon scattering when the inelastic eta-kaon channel also contributes. These studies illustrate the practicality of extracting physical scattering (S-matrix) elements from LQCD and have opened a whole new era of lattice computations of hadron dynamics.
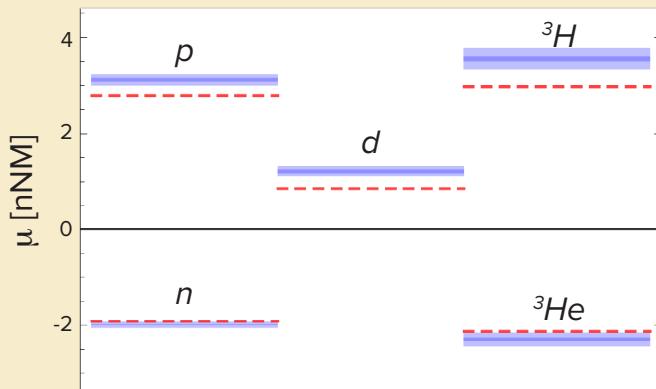
Figure 2: *In an impressive tour-de-force, scientists have now calculated the properties and structure of light nuclei with LQCD. Shown here are the magnetic moments of the proton, neutron, deuteron, ^{3}He, and triton. The red dashed lines show the experimentally measured values. The solid bands are the result of LQCD calculations with a pion mass of 805 MeV.*

It has even become possible to calculate the properties of light nuclei. Nuclear scientists have managed to extract the magnetic moments of the lightest nuclei from LQCD calculations, with reasonable agreement with experimental values as shown in Figure 2. We anticipate, within the next several years, precision calculations of light nuclei, their properties, their structure, and their reactions.

With the growing capability to perform precise LQCD calculations of many quantities of crucial importance to the mission of nuclear physics, including the properties and structure of hadrons and light nuclei and the forces between them, we are truly entering a golden era.

(SHMS) in Hall C. As is illustrated in Figure 2.2, SHMS will nearly quadruple the momentum transfer over which the pion form factor is known. These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large- to short-distance-scale behavior.

Expressions of Chiral Dynamics in Hadrons
The special status of pions and kaons in QCD and their marked impact on the long-distance structure of hadrons can be systematically encoded in an effective theory, applicable to processes at low energy. This effective theory, as well as emerging LQCD calculations, can provide benchmark predictions for so-called polarizabilities that parameterize the deformation of hadrons due to electromagnetic fields, spin fields, or even internal color fields. Great progress has been made in determining the electric and magnetic polarizabilities. Within the next few years, data are expected from the High Intensity Gamma-ray Source (HIγS) facility that will allow accurate extraction of proton-neutron differences and spin polarizabilities. JLab also explores aspects of this physics. The most precise measurement of the neutral-pion decay rate, exactly calculable from fundamental constants, was already done at JLab, and with the 12-GeV Upgrade the pion polarizability and decays of other light pseudoscalar mesons will be measured.

Figure 2.2: *Existing (dark blue) data and projected (red, orange) uncertainties for future data on the pion form factor. The solid curve (A) is the QCD-theory prediction bridging large and short distance scales. Curve B is set by the known long-distance scale—the pion radius. Curves C and D illustrate calculations based on a short-distance quark-gluon view.*

The 1D Picture of How Quarks Move within a Hadron
Whereas form factors provide a picture of hadrons as a whole, a technique called deep inelastic scattering (DIS) is used to access their quark substructure. In DIS, high-energy electrons scatter hard off individual quarks, and the proton or neutron is essentially destroyed in the collision. By measuring the angle of the scattered electron and the energy it loses in the collision, it is possible to discern the fraction of the nucleon's momentum that was carried by the struck quark. This fraction is referred to as the *longitudinal* momentum fraction *x*. The probability of finding a quark with a specific momentum fraction *x* is what is referred to as a parton distribution function (PDF). In short, the PDFs provide us with a one-dimensional (1D) picture describing the motion of the quarks within the hadron.

In DIS, the momentum fraction x of the quark off which an electron scatters provides insight into whether the quark was most likely a valence quark (larger values of x) or a sea quark (smaller values of x). Naively, if a hadron were composed of three quarks, we might expect each quark to carry about 1/3 of the momentum. Because the quarks are bound and exchanging gluons, however, they can carry a momentum fraction anywhere from 0 to 1. JLab turns out to be an excellent place to study the valence-quark region, very roughly from around 0.1 up to values approaching unity.

The Quark Valence Structure
One feature of the valence quark structure that is of particular interest is the ratio d(x)/u(x) in the limit of the momentum fraction x approaching one. Here d(x) and u(x) are the PDFs for the d and u quarks, respectively. While in general it is not yet possible to calculate PDFs from first principles, near x=1, there are some definite model predictions for the ratio of d/u, making such a measurement a powerful test of our understanding of hadronic structure within QCD.

The ratio d/u will be measured (see Figure 2.3) using the 12-GeV upgraded CEBAF in multiple ways. In the early years, it will be measured by comparing scattering from the mirror nuclei ^{3}He and ^{3}H, as well as by handpicking events where the scattering takes place off a near-free neutron in ^{2}H. Later, the ratio can be accessed by measuring the aforementioned parity-violating effect in DIS with the foreseen SoLID detector.
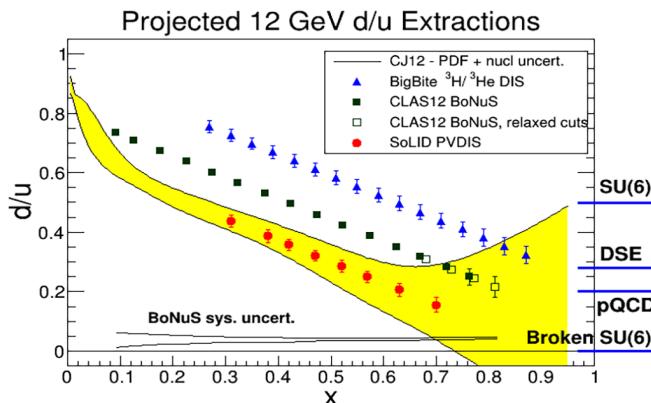
Figure 2.3: *Projected uncertainties (offset for display) for JLab 12-GeV measurements of the ratios of the PDFs for the d and u quarks at large momentum fraction x. The yellow band represents the uncertainty in the existing measurements under several theoretical assumptions. Various predictions for this ratio in the limit of x = 1 are given by the blue lines.*

Of similar interest are the spin-dependent PDFs, Δu(x) and Δd(x), that quantify the orientation of the spin

of u and d quarks. Both Δu(x)/u(x) and Δd(x)/d(x) are predicted to approach unity as the momentum fraction x approaches 1. Whether this is the case or not, and, if true, the manner in which they do so, provides important insight on nucleon structure. Measurements of these quantities at JLab provided early hints that quark orbital angular momentum plays an important role in nucleon structure. With the 12-GeV Upgrade, the spin structure of the valence region will be mapped out in exquisite detail.

The Sea Quark and Gluon Structure
In atomic systems, the particle-antiparticle pairs induced by quantum fluctuations play a relatively minor role. In contrast, in strong interactions, quark-antiquark pairs are readily produced as a result of the relatively large magnitude of the strong force, and they form an integral part of the nucleon's structure.

While JLab will measure the ratio d/u for the valence quarks, other experiments will measure a similar ratio for the light (sea) antiquarks, $\bar{d}/\bar{u}$. This ratio was originally assumed to be unity, as quantum fluctuations are creating both. Experiments using the Drell-Yan process (in which a quark from one nucleon annihilates with a sea antiquark from another nucleon) observed $\bar{d}$ quarks to be more prevalent than $\bar{u}$ quarks, a smoking gun for a definite role of sea quarks in nucleon structure. SeaQuest at Fermi National Accelerator Laboratory (FNAL) exploits this process to measure $\bar{d}/\bar{u}$ to higher values of x, a region where $\bar{u}$ may well become prevalent. A proposal is being discussed to upgrade SeaQuest with a polarized beam and target that could point to whether light sea quarks have orbital angular momentum.

At RHIC, the production of W bosons in polarized proton-proton collisions serves as an elegant tool to study both the unpolarized and the spin-dependent PDFs for intermediate regions of the momentum fraction x. The data from RHIC have provided the first evidence that the spin carried by $\bar{u}$ quarks (Δ$\bar{u}$) differs from that of $\bar{d}$ quarks (Δ$\bar{d}$) as evidenced in Figure 2.4, which shows a global analysis incorporating RHIC data. This asymmetry between u and d quarks in the sea again underscores the role of sea quarks in nucleon structure. As discussed in Sidebar 2.6 of the EIC subchapter, the RHIC program has also led to our first glimpse of the quantity known as ΔG, the fraction of the proton spin carried by the intrinsic spin of the gluons. This important development, indicating that ΔG is nonzero and positive,

represents the first fruit of more than a decade of effort in this direction.
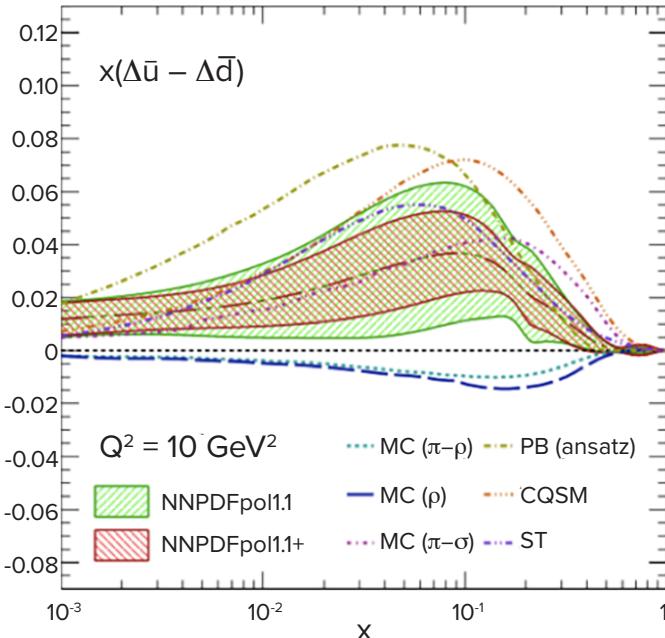
Figure 2.4: *The difference between the $\Delta\bar{u}$ and $\Delta\bar{d}$ spin functions as extracted from the NNPDF global analysis. The green (red) band shows the present (final expected) uncertainties from analysis of the RHIC W data set. Various model calculations are also shown.*

A Multidimensional View of Nucleon Structure

"With 3D projection, we will be entering a new age. Something which was never technically possible before: a stunning visual experience which 'turbocharges' the viewing." This quotation from film director J. Cameron could just as well describe developments over the last decade or so in hadron physics, in which a multidimensional description of nucleon structure is emerging that is providing profound new insights. Form factors tell us about the distribution of charge and magnetization but contain no direct dynamical information. PDFs allow us to access information on the underlying quarks and their longitudinal momentum but tell us nothing about spatial locations. It has now been established, however, that both form factors and PDFs are special cases of a more general class of distribution functions that merge spatial and dynamic information. Through appropriate measurements, it is becoming possible to construct "pictures" of the nucleon that were never before possible.

3D Spatial Maps of the Nucleon: GPDs
Some of the important new tools for describing hadrons are Generalized Parton Distributions (GPDs). GPDs can be investigated through the analysis of *hard exclusive processes*, processes where the target is probed

by high-energy particles and is left intact beyond the production of one or two additional particles. Two processes are recognized as the most powerful processes for accessing GPDs: deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP) where a photon or a meson, respectively, is produced.

One striking way to use GPDs to enhance our understanding of hadronic structure is to use them to construct what we might call 3D spatial maps (see Sidebar 2.2). For a particular value of the momentum fraction *x*, we can construct a spatial map of where the quarks reside. With the JLab 12-GeV Upgrade, the valence quarks will be accurately mapped.

GPDs can also be used to evaluate the total angular momentum associated with different types of quarks, using what is known as the Ji Sum Rule. By combining with other existing data, one can directly access *quark orbital angular momentum*. The worldwide DVCS experimental program, including that at Jefferson Lab with a 6-GeV electron beam and at HERMES with 27-GeV electron and positron beams, has already provided constraints (albeit model dependent) on the total angular momentum of the u and d quarks. These constraints can also be compared with calculations from LQCD. Upcoming 12-GeV experiments at JLab and COMPASS-II experiments at CERN will provide dramatically improved precision. A suite of DVCS and DVMP experiments is planned in Hall B with CLAS12; in Hall A with HRS and existing calorimeters; and in Hall C with HMS, the new SHMS, and the Neutral Particle Spectrometer (NPS). These new data will transform the current picture of hadronic structure.

3D Momentum Maps of the Nucleon: TMDs
Other important new tools for describing nucleon structure are transverse momentum dependent distribution functions (TMDs). These contain information on both the longitudinal and transverse momentum of the quarks (and gluons) inside a fast moving nucleon. TMDs link the transverse motion of the quarks with their spin and/or the spin of the parent proton and are, thus, sensitive to orbital angular momentum. Experimentally, these functions can be investigated in proton-proton collisions, in inclusive production of lepton pairs in Drell-Yan processes, and in *semi-inclusive deep inelastic scattering* (SIDIS), where one measures the scattered electron and one more meson (typically a pion or kaon) in the DIS process.
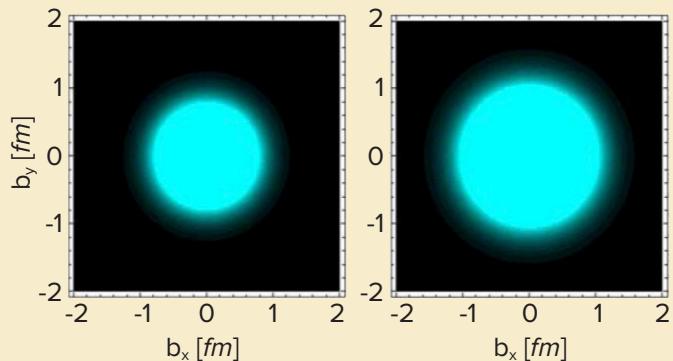
Sidebar 2.2: The First 3D Pictures of the Nucleon

A computed tomography (CT) scan can help physicians pinpoint minute cancer tumors, diagnose tiny broken bones, and spot the early signs of osteoporosis. Now physicists are using the principles behind the procedure to peer at the inner workings of the proton. This breakthrough is made possible by a relatively new concept in nuclear physics called generalized parton distributions.

An intense beam of high-energy electrons can be used as a microscope to look inside the proton. The high energies tend to disrupt the proton, so one or more new particles are produced. Physicists often disregarded what happened to the debris and measured only the energy and position of the scattered electron. This method is called inclusive deep inelastic scattering and has revealed the most basic grains of matter, the quarks. However, it has a limitation: it can only give a one-dimensional image of the substructure of the proton because it essentially measures the momentum of the quarks along the direction of the incident electron beam. To provide the three-dimensional (3D) picture, we need instead to measure all the particles in the debris. This way, we can construct a 3D image of the proton as successive spatial quark distributions in planes perpendicular to its motion for slices in the quark's momentum, just like a 3D image of the human body can be built from successive planar views.

An electron can scatter from a proton in many ways. We are interested in those collisions where a high-energy electron strikes an individual quark inside the proton, giving the quark a very large amount of extra energy. This quark then quickly gets rid of its excess energy, for instance, by emitting a high-energy photon. The quark does not change identity and remains part of the intact target proton. This specific process is called deeply virtual Compton scattering (DVCS). For the experiment to work, the scientists need to measure the speed, position, and energy of the electron that bounced off the quark, of the photon emitted by the quark, and of the reassembled proton. From this information the 3D picture of the proton can be constructed.

The first 3D views of the proton: the spatial charge densities of the proton in a plane (b_x, b_y) positioned at two different values of the quark's longitudinal momentum x: 0.25 (left) and 0.09 (right).

Very recently, using the DVCS data collected with the CLAS detector at JLab and the HERMES detector at DESY/Germany, the first nearly model-independent images of the proton started to appear. The result of this work is illustrated in the figure, where the probabilities for the quarks to reside at various places inside the proton are shown at two different values of its longitudinal momentum x (x = 0.25 left and x = 0.09 right). This is analogous to the "orbital" clouds used to depict the likely position of electrons in various energy levels inside atoms. The first 3D pictures of the proton indicate that when the longitudinal momentum x of the quark decreases, the radius of the proton increases.

The broader implications of these results are that we now have methods to fill in the information needed to extract 3D views of the proton. Physicists worldwide are working toward this goal, and the technique pioneered here will be applied with Jefferson Lab's CEBAF accelerator at 12 GeV for (valence) quarks and, later, with a future EIC for gluons and sea quarks.

In these experiments, the quark struck in the scattering process must, as it cannot exist in isolation, join with an antiquark partner or two quark partners to form new hadrons. The latter process is called fragmentation. The hadron resulting from the fragmentation process retains a memory of the original transverse motion of the quark and can, thereby, present new information about the transverse momentum dependence of the quark within the nucleon. The correlations of spin and the transverse momentum of quarks give rise to asymmetries in the distributions of the produced particles. One source of such asymmetries is the correlation between the transverse momentum of the quark and the transverse spin of the parent proton, the so-called Sivers function.

A nonzero Sivers function is considered to be strong evidence for the presence of quark orbital angular momentum. Indeed, it has been measured to be nonzero in the HERMES and JLab experiments. Figure 2.5 shows the unique potential of the JLab 12-GeV program to map the Sivers function for the up quark. The Sivers function has a quite intriguing property predicted by QCD. When measured in SIDIS, it will have one sign, yet when measured in a collision with a proton or pion beam, it should have the opposite sign. This sign change is due to the nature of QCD color interactions and provides an important test of our understanding. It is imperative that the quark Sivers functions that will be measured in SIDIS are also accurately measured with hadron beams, such as the proton beams available at RHIC or Fermilab and the pion beams used by the COMPASS-II experiment at CERN.

is independently suggested by LQCD calculations that also point to a flavor and spin dependence of transverse momentum. The JLab 12-GeV era can move this field to a new level of sophistication. Precision measurements in semi-inclusive pion and kaon production from unpolarized, as well as longitudinally and transversely polarized proton and neutron targets, will allow access to both flavor and spin dependent transverse momentum distributions in the valence quark region. Multiple instruments bring essential elements to this campaign: SBS, CLAS12, HMS-SHMS, and the proposed NPS. Finally, the proposed multipurpose SoLID detector (see Figure 2.6) would realize the full potential of the upgraded CEBAF. RHIC will contribute by utilizing transversely polarized beams to make the first measurements in hadronic collisions to probe antiquark and gluon TMDs with the forward upgrades proposed for STAR and PHENIX. These efforts will benefit from the polarized and unpolarized fragmentation results to be extracted from the e^+e^- collision data from Belle, Belle II, and Babar.
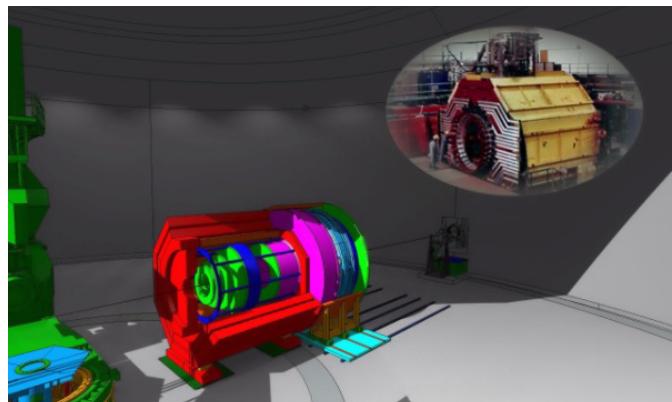
Figure 2.6: *The envisioned SoLID experiment in Hall A is centered around the CLEO-II magnet (insert) that will be relocated to JLab to enable a rich multipurpose science program. SoLID boasts large acceptance detection with operability at extremely high luminosities and offers unprecedented opportunities to provide precision 3D imaging of the motion of valence quarks in the nucleon and to probe the Standard Model.*

Figure 2.5: *Maps of the Sivers function for up quarks as a function of transverse momentum and at different values of the longitudinal momentum fraction x, as projected for 12-GeV JLab data.*

Pioneering SIDIS experiments from JLab, HERMES, and COMPASS have provided initial information about TMDs and hint that valence u and d quarks differ in their transverse momentum distributions. This behavior

HADRON SPECTROSCOPY

Atomic spectroscopy has been a crucial tool for studying the electromagnetic interactions that bind electrons to the nucleus. Likewise, hadron spectroscopy illuminates the QCD interaction that binds quarks. While the proton and neutron contain the two lightest valence quarks (up and down), other hadrons composed of these light quarks or of more massive quarks (strange, charm, and bottom) and their corresponding antiquarks can be created in energetic collisions produced by particle

accelerators. Once produced, these hadrons decay promptly, allowing one to measure only a few of their properties, such as their mass, charge, and angular momentum. Studying patterns of hadrons classified by these properties provides insight into and provokes questions about the inner workings of QCD.

The observed patterns of states suggest, perhaps surprisingly, that almost all hadrons fall into two classes: baryons that contain three valence quarks, like the proton and neutron, and mesons that contain a valence quark and a valence antiquark. In principle, QCD allows hadrons made of two quarks and two antiquarks (tetraquarks), four quarks and an antiquark (pentaquarks), and infinitely many other configurations. Recently, physicists studying the spectrum of heavy mesons formed with charm and bottom quarks have uncovered evidence that supports the existence of tetraquark and pentaquark hadrons. Understanding the properties of these new states of QCD may illuminate why nature prefers hadrons with relatively few quarks.

The Three-Quark Arena: Chasing the Missing Baryons
A major experimental initiative continues to be the search for the so-called "missing baryons." If each of the three quarks in a baryon interacted equally, one would predict the existence of more baryons than observed by experiments. The experimental data are, therefore, suggestive of a more intricate manifestation of QCD in baryons. For example, two quarks may strongly bind with each other, forming a "diquark" that interacts more weakly with the third quark. Determining whether the missing baryons really do not exist or are just not yet discovered will guide our understanding.

Jefferson Lab has been engaged in a vigorous program to search for these missing states by trying to produce them in photon-induced collisions, in contrast to most of the earlier searches using hadron beams. Analysis of recent data from JLab has substantiated the existence of five additional excited baryon states that now appear in the compilation of known hadrons published in the *Review of Particle Physics*. This breakthrough was enabled by the polarized beam and polarized target capabilities of JLab. The new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena.

The Gluon: Force Mediator and Constituent Particle?
One of the most intriguing puzzles of QCD is understanding the role that gluons play in hadrons. Gluons mediate the strong force; quarks in hadrons interact with each other by emitting and absorbing gluons. However, gluons also interact with each other, suggesting that gluons could bind together like quarks. The consequences of this unique self-interacting property of gluons should give rise to new states of matter composed entirely of gluons or quark-gluon hybrids. Recent breakthroughs in theoretical techniques have enabled physicists to perform LQCD calculations of the complete spectrum of both the conventional and experimentally elusive hybrid mesons. These calculations indicate, for the first time, that the gluonic component of hybrid mesons has specific dynamical properties, an understanding that can be tested with experimental data.

The GlueX experiment in Hall D at JLab has been designed to utilize the unique photon beam capability of the 12-GeV Upgrade to search for these hybrid mesons formed with light quarks. The JLab spectroscopy program, which is well underway with the successful operation of the GlueX detector in 2014, will be augmented by the multi-purpose CLAS12 apparatus in Hall B. Planned future detector upgrades are essential to enable a complete study of hadrons composed of all three flavors of light quarks: up, down, and strange.

The 12-GeV Upgrade of JLab will permit a detailed exploration of light quark hadrons and is the centerpiece of experimental hadron spectroscopy in the U.S. in the next decade. Collaboration with complementary facilities abroad to study hadrons composed of heavier quarks is a critical ingredient in a complete study of the spectrum. In addition, a theory-based initiative, like the Joint Physics Analysis Center at JLab, geared at developing techniques for conducting a global data analysis, will augment the experimental knowledge of the hadron spectrum. These experimental observations can then be compared to emerging QCD-based theoretical calculations to understand the role that gluons play in the structure of matter.

QCD AND NUCLEI
Nuclei are bound systems of nucleons (protons and neutrons), much like molecules are assembled from atoms. Many aspects of nuclear binding can

be described quite well through various effective interactions. However, to fully understand and predict nuclear properties, we need to find out how the binding forces between nucleons emerge from the fundamental theory of QCD and give rise to nuclei. Impressive progress in this direction has recently been achieved with LQCD (Sidebar 2.1). In addition, we need to find out how the internal QCD structure of nucleons is related to, and in turn, is affected by nuclear binding.

The Short-Range Structure of Nuclei

Of particular interest is the interaction of nucleons that are relatively close to each other, so that their internal structure might be expected to come into play. This "short-range interaction" is responsible for the fact that most nuclei have roughly the same density, and ultimately determines the stability and size of neutron stars. While nucleons mostly move at moderate speeds inside nuclei (up to 30% of the speed of light), their short-range encounters can impart significantly higher momentum to each of them and make them move swiftly in opposite directions. Such high-momentum correlations, long predicted by nuclear theory, provide an excellent way to study the short-range part of the nucleon-nucleon interaction and have recently been identified and characterized in detail by experiments at JLab.

In these experiments a fascinating feature came to light. Nearly all of the observed correlations are between two nucleons of the opposite type—one proton and one neutron—while proton-proton and neutron-neutron correlations are ten times less likely. This leads to the somewhat paradoxical result that even in heavy nuclei, where neutrons are more common than protons, the "minority" protons are more likely to be part of a high-momentum pair than the neutrons. This incredibly important feature of the nucleon-nucleon interaction has implications for the behavior of cold, dense nuclear matter in general, such as that found in a neutron star.

Quark Properties in Nuclei—The EMC Effect

If we want to understand the role of QCD in nuclei, one obvious question is how the nuclear environment affects the quark-structure of nucleons. One answer is provided by the EMC effect, named after the European Muon Collaboration that first observed it 30 years ago. They found that the probability of DIS off a quark inside a large nucleus decreases significantly with the

momentum fraction x carried by the quark over the range $x = 0.3$–0.7, relative to the same probability inside a free nucleon. This result indicates that valence quarks tend to carry a smaller fraction of the momentum of nucleons tightly bound in nuclei than in free nucleons. A full understanding of this striking EMC effect has remained elusive until now.

Recent precise data from JLab on this probability ratio in light nuclei, as shown in Figure 2.7, show a striking feature. It has long been known that the EMC effect becomes more pronounced for heavier nuclei, which seemed to indicate that it might depend on A, the total number of nucleons in the nucleus, or on the *average* nuclear density. The JLab data indicate, however, that the EMC effect depends on the *local* nuclear density. This is illustrated strikingly in the case of ^{9}Be, which can be described as two "alpha clusters" (4-nucleon configurations similar to ^{4}He nuclei) and one extra neutron. These three subunits essentially orbit in a fairly large volume, giving ^{9}Be a relatively small *average* nucleon density. Most of the nucleons off of which an electron can scatter, however, are contained in one of the two clusters, where there is a relatively high *local* nucleon density. The pronounced EMC effect in ^{9}Be strongly suggests that it is the local density that drives the modification.
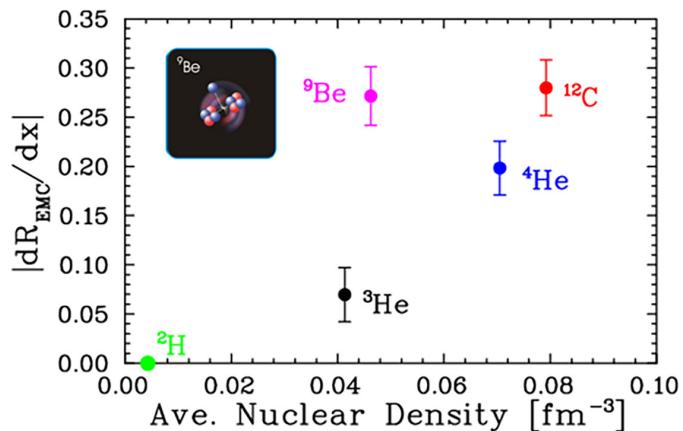
Figure 2.7: *Results from precise measurements at JLab of the slope of the EMC effect in light nuclei. They reveal that the fairly "dilute" nucleus of beryllium behaves more like the dense carbon nucleus than the similarly dilute ^{3}He nucleus, suggesting the quark distributions depend on the local rather than the average nuclear environment.*

This observation led scientists to a fascinating connection between the aforementioned two-nucleon correlations and the EMC effect in a nucleus. Put simply, the number of two-nucleon correlated pairs found in a given nucleus appears to be directly proportional to

the magnitude of the EMC effect in that same nucleus, illustrated by the straight line in Figure 2.8. This result seems to indicate that both of these effects may depend on local nuclear density or, perhaps, that nucleons in correlated high-momentum pairs have the most strongly modified quark distributions. At JLab 12-GeV, high-precision experiments will be performed to further study both of these effects in a wide variety of nuclei. Furthermore, by "tagging" some of the participants in short-range collisions, it will be possible to directly explore the connection between those two phenomena. With these data and concurrent theoretical development, we are poised to greatly improve our understanding of the interplay between nuclear binding and QCD.
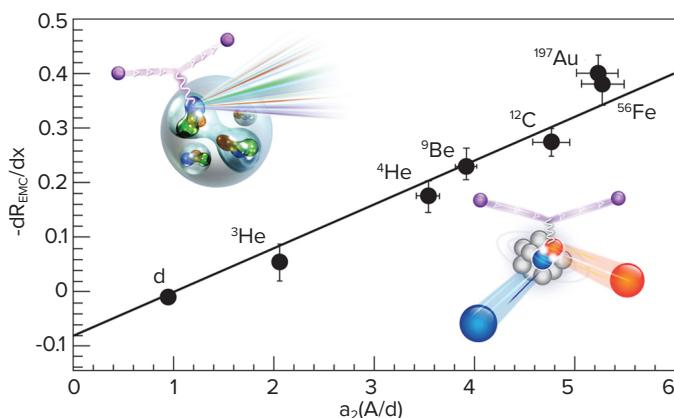
Figure 2.8: This plot illustrates, for a sample of eight nuclei, the apparent linear relationship between a parameter that characterizes the number of two-nucleon correlated pairs, $a_2(A/d)$, and the strength (i.e., the slope) of the EMC effect. A clear correlation is evidenced by the straight line that all eight nuclei fall on.

2.2 QCD and the Phases of Strongly Interacting Matter

Nuclear collisions at the RHIC and the LHC produce matter with temperatures in the trillions of degrees. In this way, scientists are recreating the matter that filled the microseconds-old universe for the purpose of characterizing its properties and understanding how it works. It was understood in the 1970s that ordinary protons and neutrons could not exist at temperatures above two trillion degrees Celsius. The predicted new form of matter, which can be recreated by heating protons and neutrons until they "melt," was named quark-gluon plasma (QGP). RHIC was built for the purpose of recreating QGP and has been doing so since 2000; the LHC was built to look for the Higgs boson and possible physics beyond the Standard Model and, at the same time, has provided the highest temperature QGP

starting in 2010. Through measurements made at RHIC and the LHC and critical advances in theory, we now have a good idea of what QGP is and how it behaves.

A huge surprise at RHIC was the discovery that QGP is a liquid, a result then confirmed at the LHC. And not just any liquid: it flows with the lowest specific viscosity (characterized in terms of the ratio of shear viscosity to entropy density η/s) of any liquid known, for example, more than ten times smaller than that of water. Over the past five years nuclear physicists have begun to quantify just how perfect the QGP liquid is by virtue of enormous progress on two primary fronts.

The tools available to produce and characterize the liquid have been dramatically enhanced. The energy range over which QGP can be studied has been extended upward by a factor of 14 with the launch of the LHC and downward by a factor of 25 with the operation of RHIC below its maximum energy. The rate of collisions at both facilities has been improved by an order of magnitude, at RHIC via an accelerator upgrade that was accomplished at 1/7th the cost anticipated at the time of the last Long Range Plan. The precision and versatility of the detector capabilities have been correspondingly upgraded.

The comparison of more extensive and sophisticated data with more advanced theory has facilitated quantitative characterization of QGP properties. The theoretical treatment of relativistic fluids, including viscosity and ripples in the initial matter density, has been developed and has successfully described the features seen in large and diverse data sets. Such comparisons have not only constrained the magnitude of η/s but are also beginning to teach us about its temperature dependence and about the nature of the ripples in the matter density originating from the colliding nuclei. Similar advances are now being made in understanding how energetic quark and gluon "probes" propagate through QGP and how the liquid responds to their passage.

As a result of these recent advances, we now know that the η/s of QGP is very close to a fundamental quantum limiting value deduced for the extreme hypothetical case when the quarks and gluons have infinitely strong interactions—an extreme that can, remarkably, be theoretically related to the physics of gravitons falling into a black hole. While QCD does, of course,

describe quark and gluon interactions, the emergent phenomenon that a macroscopic volume of quarks and gluons at extreme temperatures would form a nearly perfect liquid came as a complete surprise and has led to an intriguing puzzle. A perfect liquid would not be expected to have particle excitations, yet QCD is definitive in predicting that a microscope with sufficiently high resolution would reveal quarks and gluons interacting *weakly* at the shortest distance scales within QGP. Nevertheless, the η/s of QGP is so small that there is no sign in its macroscopic motion of any microscopic particlelike constituents; all we can see is a liquid. To this day, nobody understands this dichotomy: how do quarks and gluons conspire to form strongly coupled, nearly perfect liquid QGP?

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

This section is organized in three parts: characterization of liquid QGP, mapping the phase diagram of QCD by doping QGP with an excess of quarks over antiquarks, and high-resolution microscopy of QGP to see how quarks and gluons conspire to make a liquid.

EMERGENCE OF NEAR-PERFECT FLUIDITY

The emergent hydrodynamic properties of QGP are not apparent from the underlying QCD theory and were, therefore, largely unanticipated before RHIC. They have been quantified with increasing precision via experiments at both RHIC and the LHC over the last several years. New theoretical tools, including LQCD calculations of the equation-of-state, fully relativistic viscous hydrodynamics, initial quantum fluctuation models, and model calculations done at strong coupling in gauge theories with a dual gravitational description, have allowed us to characterize the degree of fluidity. In the temperature regime created at RHIC, QGP is the most liquidlike liquid known, and comparative analyses of the wealth of bulk observables being measured hint that the hotter QGP created at the LHC has a somewhat larger viscosity. This temperature dependence will be more tightly constrained by upcoming measurements

at RHIC and the LHC that will characterize the varying shapes of the sprays of debris produced in different collisions. Analyses to extract this information are analogous to techniques used to learn about the evolution of the universe from tiny fluctuations in the temperature of the cosmic microwave background associated with ripples in the matter density created a short time after the Big Bang (see Sidebar 2.3).

There are still key questions, just as in our universe, about how the rippling liquid is formed initially in a heavy-ion collision. In the short term, this will be addressed using well-understood modeling to run the clock backwards from the debris of the collisions observed in the detectors. Measurements of the gluon distribution and correlations in nuclei at a future EIC together with calculations being developed that relate these quantities to the initial ripples in the QGP will provide a complementary perspective. The key open question here is understanding how a hydrodynamic liquid can form from the matter present at the earliest moments in a nuclear collision as quickly as it does, within a few trillionths of a trillionth of a second.

Geometry and Small Droplets
Connected to the latter question is the question of how large a droplet of matter has to be in order for it to behave like a macroscopic liquid. What is the smallest possible droplet of QGP? Until recently, it was thought that protons or small projectiles impacting large nuclei would not deposit enough energy over a large enough volume to create a droplet of QGP. New measurements, however, have brought surprises about the onset of QGP liquid production.

Measurements in LHC proton-proton collisions, selecting the 0.001% of events that produce the highest particle multiplicity, reveal patterns reminiscent of QGP fluid flow patterns. Data from p+Pb collisions at the LHC give much stronger indications that single small droplets may be formed. The flexibility of RHIC, recently augmented by the EBIS source (a combined NASA and nuclear physics project), is allowing data to be taken for p+Au, d+Au, and ^{3}He+Au collisions, in which energy is deposited initially in one or two or three spots. As these individual droplets expand hydrodynamically, they connect and form interesting QGP geometries as shown in Figure 2.9. If, in fact, tiny liquid droplets are being formed and their geometry can be manipulated, they will provide

a new window into the earliest pre-hydrodynamic physics. Alternative explanations of the data from these experiments will also be tested.
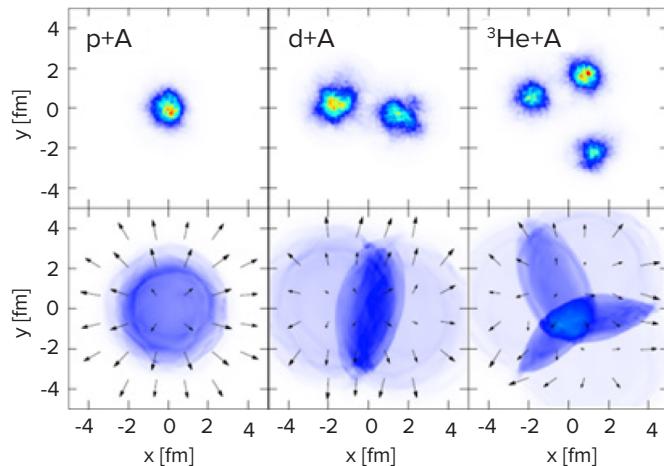
Figure 2.9: *Simulated initial energy deposition for individual collisions of protons, deuterons, and helium-3 on large nuclei (above) and the QGP geometry resulting from hydrodynamic flow (below).*

Geometry Engineering
Varying the geometry of the initial conditions—either by colliding ions of different shapes, including Cu+Au and U+U at RHIC, or by new methods used to select shape fluctuations—has enabled physicists to test models of the initial nuclear wave function in subtle ways, again complementary to future EIC measurements.

Tracers in the Flowing Liquid
In RHIC and LHC collisions, in addition to producing QGP, one produces pairs of charm–anticharm and bottom–antibottom quarks. These quarks, referred to as heavy quarks, are produced at the first moment of the collision and are only very rarely created or destroyed thereafter. They serve as test buoys in the liquid QGP. Measurements of particles containing charm quarks indicate that heavy quarks with moderate energy do, in fact, get swept up in the flowing and expanding QGP droplet. Evidence supporting this conclusion includes charm mesons having highly modified momentum distributions and having a similar elliptic flow pattern as light-quark hadrons. RHIC experiments have recently installed new cutting-edge silicon detectors that enable precision measurements of particles containing heavy quarks. In addition, key detector upgrades at LHC with strong U.S. involvement will enable higher statistics measurements in the lower momentum region where flow effects are the largest. As a result, the uncertainties

in these unique measurements will soon be reduced significantly. Measuring the flow patterns of charm and the much heavier bottom quarks separately provides important new information due to the large mass difference between them.

From Characterization to Understanding
The field has made substantial strides in the experimental characterization of liquid QGP, and new measurements and new discoveries are anticipated in the coming few years. Pursuing these directions will yield quantitative characterization of the properties of liquid QGP and of how it ripples and flows.

Advancing from characterization to understanding requires progress on two fronts. To put the properties of QGP in their natural context, we need to map the phase diagram of QGP by doping it with an excess of quarks over antiquarks and observing any changes. And to understand how quarks and gluons that interact only weakly when they are close to each other correlate in such a way that they conspire to form a nearly perfect liquid, we must probe liquid QGP at varying length scales. We need to do high resolution microscopy on QGP.

DOPING QGP WITH QUARKS TO MAP ITS PHASE DIAGRAM
In the highest energy RHIC and LHC collisions and in the early universe, liquid QGP contains almost as many antiquarks as quarks. In the language of condensed matter physics, this is undoped QGP. It would be impossible to understand strongly correlated electron systems in condensed matter physics if all we knew were their properties in the absence of doping, with equal numbers of electrons and holes. Here too, if our goal is understanding, we must map the phase diagram of QCD as a function of both temperature and doping, in this case doping QGP with an excess of quarks over antiquarks.
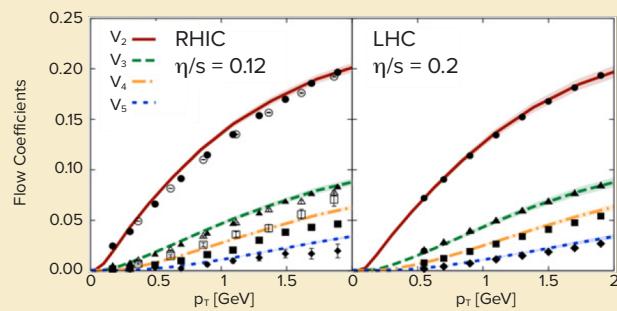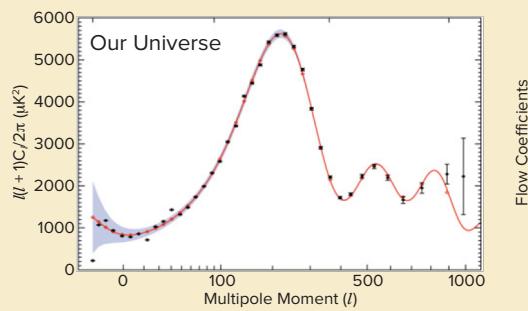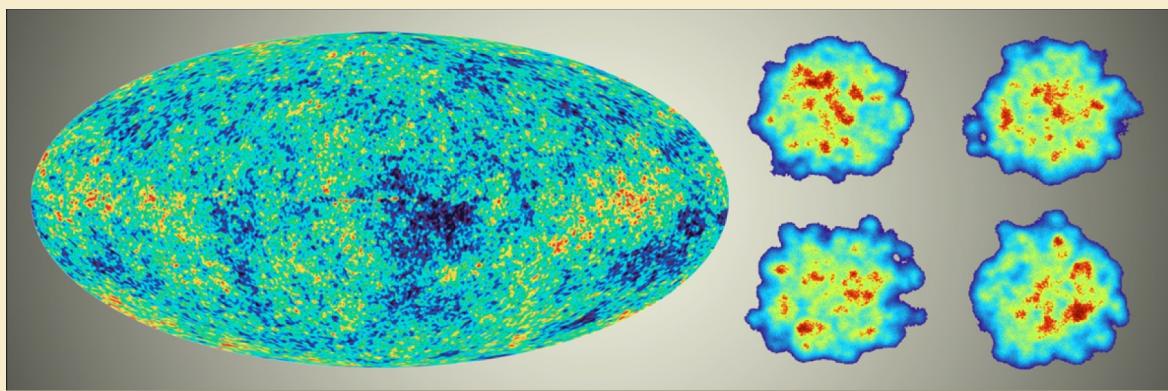
Rigorous theory calculations using lattice QCD tell us that the transition in which undoped QGP cools and forms hadrons is a rapid but smooth crossover. In contrast, QGP that is doped may experience instead a sharp first order phase transition as it cools, with bubbles of QGP and bubbles of hadrons coexisting at a critical temperature, much as bubbles of steam and water coexist in a boiling pot. At very large values of the

Sidebar 2.3: Fluctuations in the Big and Little Bangs

Fluctuations from after the Big Bang around the time atoms were first forming are preserved in time until the image at the top left is taken. Cosmologists' quantitative analysis of precise measurements (bottom-left graph) made from this image of the one Big Bang tell us key properties of the universe, for example, how much dark matter it contains. In heavy-ion collisions, nuclear physicists produce billions of "little bangs" and study their average properties and how they vary as an ensemble. These experiments, which reproduce tiny droplets of Big Bang matter for laboratory analysis, answer questions about the material properties of this liquid that cannot be accessed by astronomical measurements. The top-right images are theoretical calculations of ripples in the matter density expected in the earliest moments of four of the billion little bangs. One of the signatures of the extraordinary liquidity of QGP comes in the form of fluctuations in the patterns of particles emerging from RHIC and LHC collisions, fluctuations traced to the survival of the matter density ripples with which the QGP is born. The bottom-right figure shows a suite of precise measurements that describes the shape (elliptical, triangular, quadrangular, pentagular) of the exploding debris produced in the little bangs, together with a

quantitative theoretical analysis that describes these data and tells us key properties of QGP, for example its specific viscosity η/s. All the curves in each panel come from one theoretical calculation, with initial ripples and η/s specified. Ripples, as in the top-right figure, originate from gluon fluctuations in the incident nuclei; if QGP had a specific viscosity as large as that of water, though, these ripples would dissipate so rapidly as to disappear before they could be measured. The fact that they survive and can be seen and characterized in the shapes of the debris from the collisions, as at the bottom right, tells us about the origin of the ripples and the smallness of η/s in QGP. These data and theoretical calculations in concert show that the QGP produced at both RHIC and the LHC is a much more nearly perfect liquid than water and hint that it becomes somewhat less liquid (has a somewhat larger η/s) at the higher temperatures reached by the LHC. An increase in η/s in going from RHIC energies (and temperatures) to those of the LHC is expected: the defining characteristic of the strong interaction is that quarks and gluons interact less strongly at higher energies and temperatures, meaning that hotter QGP is expected to become a less perfect liquid.

doping, and at lower temperatures, quarks pair up with each other, forming a color superconductor. The point where the doping becomes large enough to instigate a sharp transition is referred to as the QCD critical point. It is not yet reliably known whether QCD has a critical point, nor where on its phase diagram it may reside. Lattice calculations for doped QGP are progressing but remain an outstanding challenge.

The phase diagram of QCD is illustrated in Sidebar 2.4. Nuclear scientists have the outstanding opportunity of both mapping it experimentally and relating it directly and quantitatively to our fundamental description of nature, the Standard Model.

A major effort to use heavy-ion collisions at RHIC to survey the phase diagram of QCD is now underway. Doped QGP is produced by colliding large nuclei at lower energies, where the excess of quarks over antiquarks in the incoming nuclei dominates. If a critical point exists within the experimentally accessible region, an energy scan can find it. The RHIC machine is uniquely suited for this doping scan because of the reach in chemical potential μ_B (a parameter reflecting the degree of doping) that its flexibility makes accessible, along with technical advantages of measuring fluctuation observables at a collider. RHIC is uniquely positioned in the world to discover a critical point in the QCD phase diagram if nature has put this landmark in the experimentally accessible region. RHIC completed the first phase of such an energy scan (Beam Energy Scan I, BES-I) in 2014, producing droplets of QGP with eight values of the doping. The region of the phase diagram being mapped out is shown in Sidebar 2.4 (figure, upper right). In the longer term, the FAIR facility at GSI will extend this search to even higher μ_B if its lower collision energies produce matter at the requisite temperatures.

Data from BES-I provide qualitative evidence for a reduction in the QGP pressure, with consequences for flow patterns and droplet lifetimes that have long been anticipated in collisions that form QGP not far above the crossover region. (See second panel of Figure 2.10.) A key obstacle to drawing quantitative conclusions is that, of necessity to date given the small samples of collisions at each of the lower energies, each measurement averages over collisions with a wide range of impact parameters.

The experimental search for the QCD critical point hinges on the fact that matter near such a point exhibits well understood critical fluctuations, which in terrestrial examples turn a clear liquid opalescent. The collision energy dependence of a fluctuation observable that is particularly sensitive to the critical point is shown in the third panel of Figure 2.10. As the doping increases, the fluctuations near a critical point are predicted to make this observable swing below its baseline value of 1.0 as the critical point is approached, then going well above, with both the dip and the rise being greatest in head-on collisions and in analyses that record as many particles as possible in each event. The new data are tantalizing, with a substantial drop and intriguing hints of a substantial rise for the lowest energy collisions. This may be indicative of the presence of a critical point in the phase diagram of QCD, although the uncertainties at present are too large to draw conclusions.

The present reach of LQCD calculations is illustrated by the yellow band on the phase diagram in Sidebar 2.4. These calculations become more challenging with increased doping, but they do indicate that the critical point is not found in the region of the phase diagram with low doping (μ_B below 200 MeV), corresponding to collisions with energy above 20 GeV. This behavior, together with the intriguing non-monotonic collision energy dependence of various observables seen at lower collision energies, corresponding to higher doping, provides strong motivation for the second phase of the RHIC Beam Energy Scan (BES-II), which will focus on building up much larger samples of collisions with energies at and below 20 GeV.

RHIC accelerator physicists are upgrading the machine to use electrons to "cool" lower energy beams in the machine (keeping the bunches of nuclei in them compact) in order to increase the luminosity at BES-II energies by about a factor of 10. The detector upgrades planned for BES-II focus on maximizing the fraction of the particles in each collision that are measured, which is particularly important for fluctuation observables. The top panel in Figure 2.10 shows the projected increases in the number of events, and the lower panels show the improved statistical precision for flow and fluctuation observables that result from the statistics together with the extended coverage from targeted detector improvements.

The trends and features in BES-I data provide compelling motivation for a strong and concerted theoretical response, as well as for the experimental measurements with higher statistical precision from BES-II. The goal of BES-II is to turn trends and features into definitive conclusions and new understanding. This theoretical research program will require a quantitative framework for modeling the salient features of these lower energy heavy-ion collisions and will require knitting together components from different groups with experience in varied techniques, including LQCD, hydrodynamic modeling of doped QGP, incorporating critical fluctuations in a dynamically evolving medium, and more.

Experimental discovery of a critical point on the QCD phase diagram would be a landmark achievement. The goals of the BES program also focus on obtaining a quantitative understanding of the properties of matter in the crossover region of the phase diagram, where it is neither QGP nor hadrons nor a mixture of the two, as these properties change with doping.

Additional questions that will be addressed in this regime include the quantitative study of the onset of various signatures of the presence of QGP. For example, the chiral symmetry that defines distinct left- and right-handed quarks is broken in hadronic matter but restored in QGP. One way to access the onset of chiral symmetry restoration comes via BES-II measurements of electron-positron pair production in collisions at and below 20 GeV. Another way to access this, while simultaneously seeing quantum properties of QGP that are activated by magnetic fields present early in heavy collisions, may be provided by the slight observed preference for like-sign particles to emerge in the same direction with respect to the magnetic field. Such an effect was predicted to arise in matter where chiral symmetry is restored. Understanding the origin of this effect, for example by confirming indications that it goes away at the lowest BES-I energies, requires the substantially increased statistics of BES-II.

Figure 2.10: *The top panel shows the increased statistics anticipated at BES-II; all three lower panels show the anticipated reduction in the uncertainty of key measurements. RHIC BES-I results indicate nonmonotonic behavior of a number of observables; two are shown in the middle panels. The second panel shows a directed flow observable that can encode information about a reduction in pressure, as occurs near a transition. The third panel shows the fluctuation observable understood to be the most sensitive among those measured to date to the fluctuations near a critical point. The fourth panel shows, as expected, the measured fluctuations growing in magnitude as more particles in each event are added into the analysis.*

NEW MICROSCOPES ON THE INNER WORKINGS OF QGP

To understand the workings of QGP, there is no substitute for microscopy. We know that if we had a sufficiently powerful microscope that could resolve the structure of QGP on length scales, say a thousand times smaller than the size of a proton, what we would see
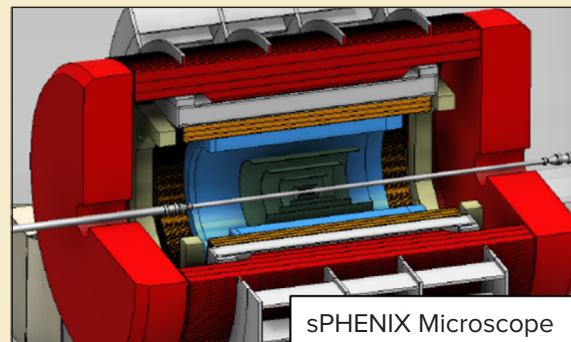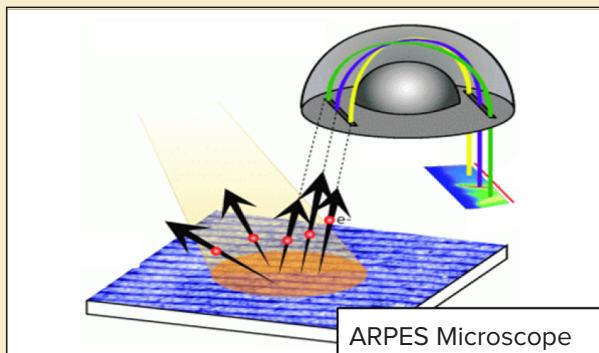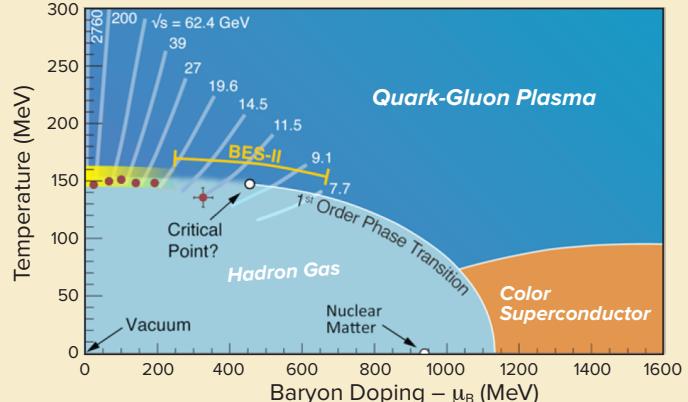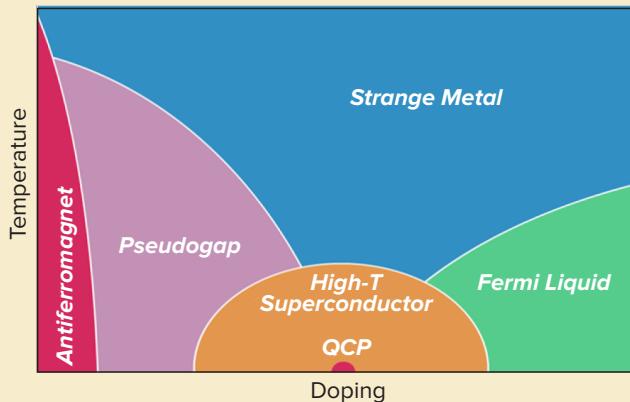
are quarks and gluons interacting only weakly with each other. The grand challenge for this field in the decade to come is to understand how these quarks and gluons conspire to form a nearly perfect liquid.

Microscopy requires suitable messengers that reveal what is happening deep within QGP, playing a role analogous to light in an ordinary microscope. The

Sidebar 2.4: The States of QCD Matter

The study of states of matter governed by the strong force parallels progress in other fields of matter in which surprising "emergent phenomena," striking macroscopic phenomena in no way apparent in the laws describing the interactions between microscopic constituents, have been discovered. High temperature superconductivity is an emergent phenomenon arising in strongly correlated, electromagnetically interacting matter. The first goals after its discovery included the mapping of its phase diagram, shown at the upper-left, and the characterization of the newly found phases of matter, including the strange metal phase. As with QGP, there is no known way to describe its structure and properties particle by particle; understanding strange metals remains a central challenge. Experimental progress can come by changing the material doping—adding more holes than electrons—and by probing the material at shorter wavelengths—for example, with the

angle resolved photo emission spectroscopy (ARPES) technique, shown on the lower left—with the goal of understanding how strong correlations result in the emergence of the surprising macroscopic phenomena. Near perfect fluidity is an equally exciting and unexpected emergent phenomenon, in this case arising in strongly interacting matter in the QGP phase. Doping QGP, adding more quarks than antiquarks, is done via changing the collision energy and enables a search for a possible critical point in the phase diagram shown in the upper right. The reach of the RHIC BES-II program that will be enabled by new instrumentation at RHIC is shown, as are the trajectories on the phase diagram followed by the cooling droplets of QGP produced in collisions with varying energy. The microscopy of QGP is enabled by new "microscopes," such as sPHENIX, shown in the lower right, and upgraded detectors and luminosities in the combined RHIC and LHC program.

ARPES Microscope

sPHENIX Microscope

messengers we describe here are heavy quark bound states which characterize the nature of QGP on three different length scales, as well as jets, which further characterize the liquid and provide the best path to true microscopy that is presently envisioned.

Characterizing QGP on Three Length Scales at Once

Bound states of a heavy quark and antiquark, referred to as quarkonia, are particularly interesting because if they are small enough in size, which is to say if they are sufficiently tightly bound, they are predicted to survive immersion in QGP. If they are larger, however, the QGP that gets between the quark and antiquark is predicted to make the quarkonia melt away, analogous to the way molecules dissociate in electromagnetic plasmas. Studying the survival probabilities of quarkonia of different sizes characterizes QGP on different length scales. In the case of the J/ψ, the most bound state of a charm and anticharm quark, there is a large suppression of these particles in RHIC collisions as expected. In the higher temperature QGP created in LHC collisions, the suppression is less. This represents very strong evidence that, despite melting at early times, new J/y mesons re-form between new partner charm and anticharm quarks late in the collision.

The newly-won understanding of charm-anticharm quarkonia sets the table for the case of bottom and antibottom quarks that bind to form upsilon particles. Three different upsilon states, with three different sizes, can be measured in heavy-ion collisions using the same techniques. First measurements of these upsilon states at the LHC follow the ordering expected if the QGP produced in LHC collisions is unable to melt the smallest upsilons but can melt the larger ones. Higher statistics measurements to come will enable checks of how these patterns depend upon the momentum of the quarkonia and the collision geometry.

Upsilons have also been detected at RHIC, and their measurement will be improved by new upgrades to the STAR detector in the near future. Ultimately, one will need very precise data, as shown in Figure 2.11, which are enabled by the sPHENIX detector. The comparison with similarly precise data from the LHC will allow us to cleanly detect the temperature dependence of how QGP screens the quark-antiquark force on three different length scales.
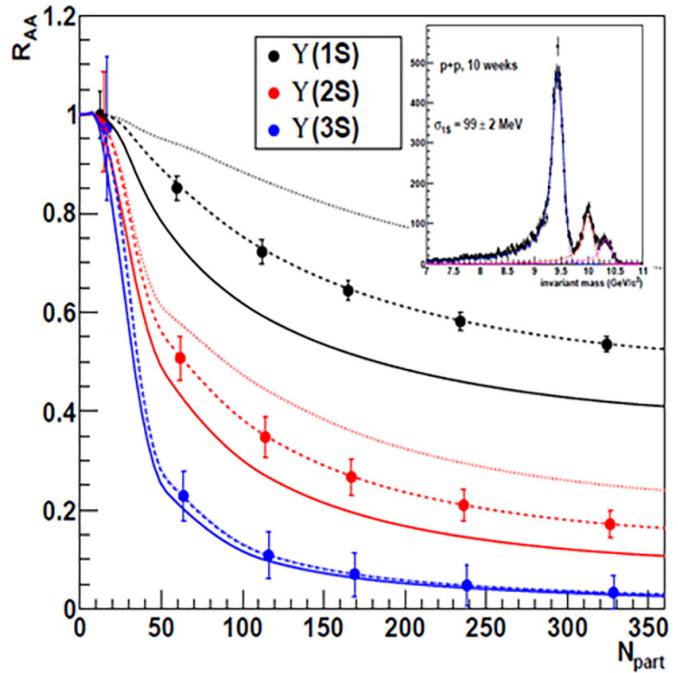
Figure 2.11: *The projected sPHENIX mass separation of the three upsilon states (in the inset) and the projected accuracy of measuring their nuclear suppression in collisions with varying impact parameters. Three sets of theory curves show the melting dependence on the degree of fluid perfection.*

Jets as Probes of QGP

At the earliest moment of a heavy-ion collision, occasionally two quarks or gluons have a "hard scattering" in which they are kicked in opposite directions that are very different from the direction of the beam in which they flew in. These quarks and gluons find themselves moving at very high velocities through the liquid QGP made in the collision, thus providing crucial characterizations of its properties. Early in the RHIC program, it was a major discovery that these partons lose significant energy as they pass through QGP, a phenomenon referred to as "jet quenching." The name comes from the fact that if these partons were produced in vacuum, they would fragment into a collimated spray, or "jet," of hadrons.

At the LHC, the higher rate of these hard scattering events combined with detectors with large acceptance yielded the first results for heavy-ion collisions where the energy carried by all the hadron fragments could be assembled to fully reconstruct the jets. Figure 2.12 shows the power of the large coverage and the clear energy imbalance between one jet and its barely visible partner jet, suggesting an event in which the two back-to-back partons had to traverse differing lengths of QGP.
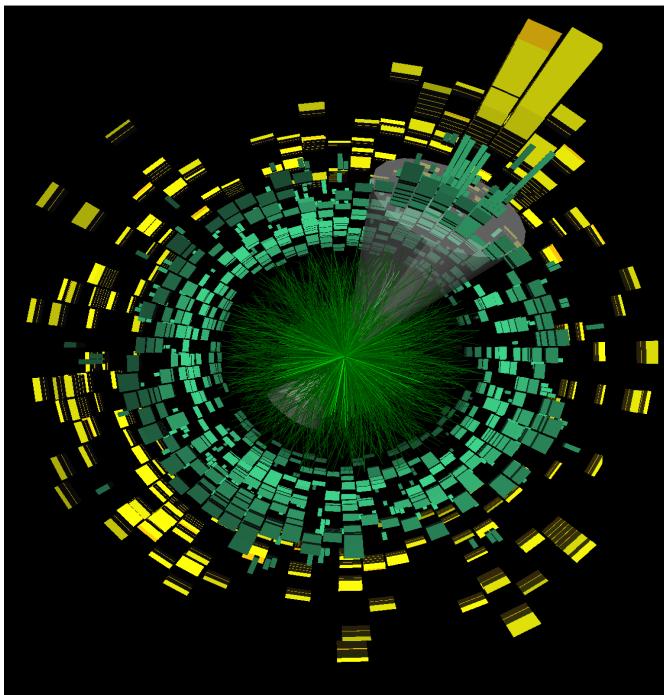
Figure 2.12: *A single LHC heavy-ion collision with one high energy jet (upper right) and no apparent partner jet—because it has been quenched by the QGP produced in the collision.*

The combined RHIC and LHC results on single hadron suppression (the fate of the most energetic particle emerging from the jet) have, in concert, been a powerful tool. Keys to their utility include: (i) the fact that the measurement ranges are complementary but overlap, (ii) the different physics from different temperature QGP created in collisions with different energies, and (iii) the different kinematics of the jets. These results have been compared with theoretical calculations where the leading parton loses energy via induced radiation. As the parton traverses the medium, it is jostled and, just as electric charges that undergo acceleration radiate photons, jostled color charges radiate gluons. The jostling and the consequent radiation and energy loss are parameterized via the same "jet quenching parameter"; a recent major accomplishment has been to reduce the uncertainty on this parameter by an order of magnitude, revealing stronger jostling in the QGP produced at RHIC than in the hotter QGP at the LHC. This analysis required a substantial theoretical effort involving the development and deployment of state-of-the-art calculations of the dynamics of the expanding droplet and of parton energy loss. A DOE Topical Collaboration played a key role by bringing people with varied, and needed, expertise together effectively, with common goals to attack these problems. Further steps in the direction of true microscopy require the analysis of a wealth of fully reconstructed jet observables, to which we now turn.

Jets as Microscopes on the Inner Workings of QGP

Just as condensed matter physicists seek to understand how strange metals with no apparent particulate description arise from interacting electrons, nuclear physicists must understand how a nearly perfect liquid arises from matter which, at short distance scales, is made of weakly interacting quarks and gluons. This will require new microscopes trained upon QGP together with theoretical advances. Jets provide tools of great potential for microscopy because their modification as they travel through QGP is influenced by the structure of the medium at many length scales. However, measuring the modifications to the "shapes" of jets and extracting information about the structure of QGP at different length scales from such data present both experimental and theoretical challenges.

Although the full promise of jets as microscopes has yet to be realized, the qualitative lessons learned to date from fully reconstructed jets at the LHC are encouraging. These studies have shown that the interaction of a jet with the medium does not detectably alter the direction of the jet as a whole and that while the energy loss is substantial, the depleted jets that emerge from the droplet are not substantially modified in other respects. They have shown that the energy lost by the jet as it traverses liquid QGP ends up as many low-momentum particles spread over angles far away from the average jet direction, i.e., as a little bit more QGP. At a qualitative level, these observations are consistent with expectations for how jets should behave in strongly coupled plasma, expectations that are based upon calculations done in model systems that can be analyzed via mapping questions about jets onto questions about strings in an equivalent gravitational description. At the same time, many attributes of the jets that emerge from QGP are described very well at weak coupling, for example, the fact that they have quite similar fragmentation patterns and angular shapes as jets that form in vacuum. This makes us optimistic that jets encode information about the structure of QGP over a wide range of length scales.

One path to realizing the potential of jets as microscopes is illustrated in Sidebar 2.5. The pointlike quarks and gluons that become visible if the microscopic structure of QGP can be resolved make it more likely that jets, or
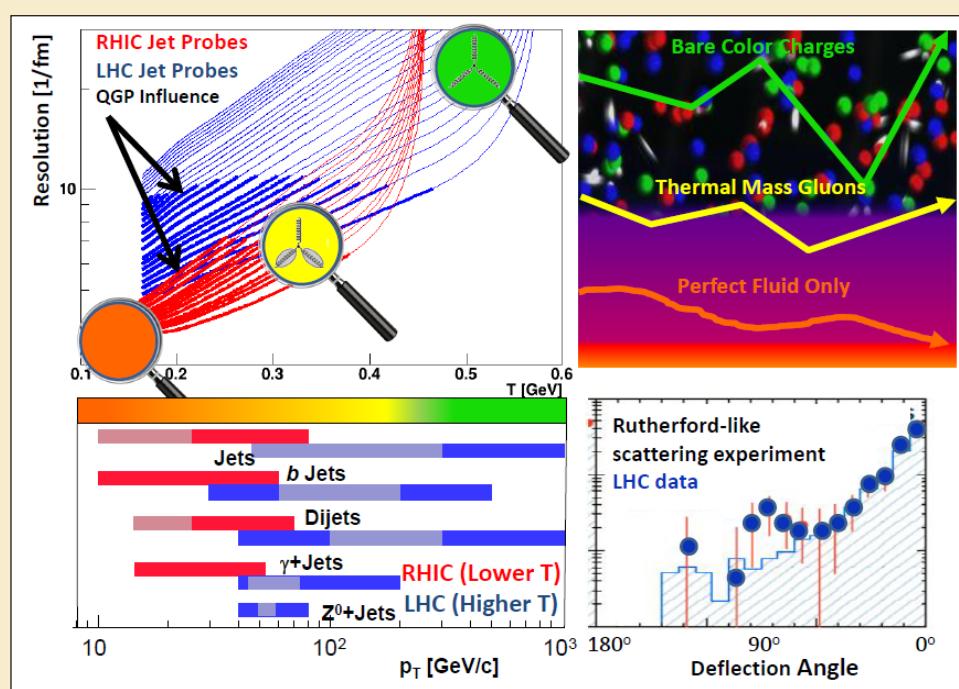
Sidebar 2.5: Jetting through the Quark-Gluon Plasma

Understanding how quark-gluon plasma (QGP) works requires new microscopy using energetic quark probes called "jets," generated in the initial interaction of the colliding beams. These high-energy quarks are initially able to "see" the very short distance structure of the medium they traverse. As they propagate, they rapidly shed energy by splitting off lower energy partons and, as this happens, the length scale that they "see" grows rapidly. The combination of all these partons eventually forms the hadrons that together make up a jet. The curves in the top-left panel illustrate how the resolving power (inverse of length scale) of jets at the LHC and RHIC decreases (symbolically, from green to yellow to orange) as they propagate and as the QGP in which they are propagating cools. The highest energy jets at the LHC probe very short wavelengths, where they should resolve the individual weakly coupled "bare" quarks and gluons (green). A key area is the lowest energy jets, optimally measured at RHIC, that probe longer wavelengths toward the scale of the nearly perfect liquid itself (orange). The curves are heavier in the regime where the resolving power of the jets is determined largely by the medium itself. The bottom-left panel shows the momentum range, related to the resolving power, of many jet observables in current measurements (muted red and blue) and the enormously increased reach at both RHIC (bright red) and the LHC (bright blue)

enabled by upgrades including the sPHENIX microscope at RHIC.

A century ago, Ernest Rutherford discovered atomic nuclei by aiming a beam of alpha particles at a gold foil and observing that they were sometimes scattered at large angles. The simplest way to "see" pointlike quarks and gluons within QGP is, as Rutherford would have understood, to look for evidence of jets, or partons within jets, scattering off individual quarks and gluons as they plow through QGP. As the top-right panel illustrates, partons that can resolve the microscopic structure of QGP are more likely to be deflected by larger angles than the partons with less resolving power that only see the nearly perfect liquid. First exploratory measurements of the jet deflection angle are now being carried out at the LHC (lower-right, where the sharp peak at the right-hand edge of the plot corresponds to undeflected jets) and at RHIC. Full exploitation of Rutherford-like scattering experiments requires the capabilities of sPHENIX at RHIC as well as upgrades to the LHC and its detectors.

Understanding the evolution of the microscopic substructure of QGP as a function of scale will complete the connection between the fundamental laws of nature, QCD, and the emergent phenomena discovered at RHIC.

The 2015 Long Range Plan for Nuclear Science

at least partons within jets, are occasionally deflected by larger angles than would be the case if the liquid had no particulate structure on any length scale. Seeing such an effect will require precise measurements of modifications of the jet structure in angular and momentum space. It can be seen by selecting particles within a narrow range of momenta within a jet of a given initial energy and measuring how their angular distribution differs from that in jets in vacuum with the same initial energy. This program requires large samples of jets in different energy regimes, with tagging of particular initial states, for example, in events with a jet back-to-back with a photon. As Sidebar 2.5 indicates, the full power of this new form of microscopy will only be realized when it is deployed at both RHIC and the LHC, as jets in the two regimes have complementary resolving power and probe QGP at different temperatures, with different values of the length scale at which bare quarks and gluons dissolve into a nearly perfect liquid.

New instrumentation at RHIC in the form of a state-of-the-art jet detector (referred to as sPHENIX) is required to provide the highest statistics for imaging the QGP right in the region of strongest coupling (most perfect fluidity) while also extending the kinematic reach at RHIC (as illustrated in Figure 2.13) to overlap that for jets at LHC energies. Upgrades to the LHC luminosities and detector and measurement capabilities are keys to providing a complete picture, as are new experimental techniques being developed to compare how light quark jets, heavy quark jets, and gluon jets "see" QGP. In general, using common, well-calibrated, jet shape observables in suitably tagged fully reconstructed jets at RHIC and the LHC will be critical to using the leverage in resolution and temperature that the two facilities provide in concert (see Sidebar 2.5) to relate observed modifications of jets to the inner workings of QGP.

OUTLOOK

The discoveries of the past decade have posed or sharpened questions that are central to understanding the nature, structure, and origin of the hottest, most nearly perfect form of liquid matter ever seen in the universe. Much remains to be learned about how the remarkable properties of this liquid change across its phase diagram and how they emerge from interactions of individual quarks and gluons. A program to complete the search for the critical point in the QCD phase
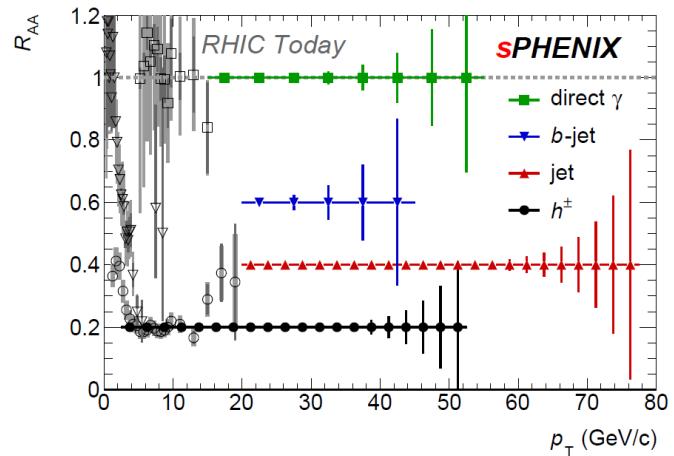
Figure 2.13: *Future reach of four precision measurements via jets for probing the most strongly coupled liquid with sPHENIX, in color, compared to current measurements from RHIC where available, in grey.*

diagram and to exploit the newly realized potential of exploring QGP structure and properties at multiple length scales at RHIC and the LHC, enabled by targeted new experimental capabilities and critical advances on a range of theoretical frontiers, places key answers within reach.

2.3 Understanding the Glue That Binds Us All: The Next QCD Frontier in Nuclear Physics

Nuclear matter in all its forms—from protons and neutrons, to atomic nuclei, to neutron stars, to quark-gluon plasma—is a teeming many-body system of quarks, antiquarks, and gluons interacting with one another via nature's strongest force. In atomic, molecular, and condensed matter systems, where the electrically charged constituents interact by exchanging photons, it is not necessary to consider the photons themselves as important constituents of the matter. In sharp contrast, the force carriers in QCD—the gluons—are constituents that play a pivotal role in determining how the properties of nuclear matter emerge from the underlying theory

The difference arises because the gluons, in addition to being exchanged between quarks, possess the intrinsic property—color charge—that is responsible for the QCD interaction, while photons are free of electric charge. The gluons thus interact among themselves and can spawn more gluons or quark-antiquark pairs (sea quarks), a fundamental feature of QCD. The emergent interactions of quarks and gluons are, for example, responsible for the fact that massive neutrons

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and protons—indeed, nearly all the mass of the visible universe—can be built up from an assembly of massless gluons and nearly massless quarks.

In order to understand how the properties and structure of nuclear matter emerge from the dynamics encoded in QCD, it is essential to precisely image gluons and sea quarks and to understand the role they and their interactions play in protons, neutrons, and nuclei. For example, we do not know how gluons are distributed in space; are they confined to the same volume as the quarks within protons and neutrons? Understanding how the gluons are distributed in space and in momentum in the nucleon will offer the first dramatic glimpse of the gluon's orbital angular momentum contribution to the nucleon's spin (see Sidebar 2.6) and provide essential clues toward understanding the important QCD phenomenon of confinement.

Gluons are special in that they can split into two or more gluons that share the parent gluon's momentum. This splitting leads to a proliferation of low-momentum gluons in normal nuclear matter: the lower the momentum of the constituents observed, the larger the number of gluons we see (see Sidebar 2.7). These low-momentum gluons are so abundant that they can make significant cumulative contributions to such static properties of the proton and neutron as mass and spin, even if each individual gluon contributes little.

The gluon proliferation has to be bounded in order to prevent runaway growth in the probability of neutron and proton interactions at high energy. QCD provides a natural self-defense mechanism because two or more gluons can also recombine. It is predicted that, at very high gluon densities, the probability for gluons to recombine will counterbalance the probability for gluons to split, leading to saturation of the gluon density and to a form of gluonic matter with universal properties that occurs inside nucleons and other hadrons, as well as inside all nuclei. When the density saturates, the gluons are anticipated to act collectively, rather than independently, presenting themselves as an intense color field to a high-energy probe.

It seems counterintuitive that electron scattering, long used to great effect in the study of nuclear structure, should also provide a precise probe for gluons and gluon-dominated matter, which carry no electric charge. But both the photon exchanged in the electron

scattering process and the gluons can fluctuate into quark-antiquark pairs, which can interact either through their electric or color charges. The interactions via these intermediary quark-antiquark pairs are now understood sufficiently well to permit the precise extraction of the distributions of gluons.

Thus, in order to probe the role of gluons and sea quarks and discover if nature adheres to the predictions of dense, and ultimately saturated, gluon matter, a new accelerator facility is required: the Electron Ion Collider. The EIC must make a qualitative leap in technical capabilities beyond previous electron scattering programs. It must reach collision energies far higher than are available at the upgraded CEBAF. It will surpass the earlier electron-proton collider HERA at DESY in Hamburg, Germany, by providing the following capabilities:

- Spin-polarized proton and light ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin;

- Heavy-ion beams to reach much higher gluon densities than with proton beams, providing the essential discovery potential to approach and reach the gluon saturation regime;

- Extensive energy variability to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter;

- Collision rates (luminosity) 100–1000 times higher, allowing unprecedented three-dimensional imaging of the gluon and sea quark distributions in order to explore correlations among them.

By precisely imaging gluons and sea quarks inside the proton and nuclei, the EIC will address some of the deepest issues regarding the emergence of nuclear properties from QCD:

- How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?

- What happens to the gluon density in nuclei at high energy? Does it saturate, giving rise to a gluonic matter component with universal properties in all nuclei, even the proton?

- How do gluons and sea quarks contribute to the nucleon-nucleon force, as manifested in the internal landscape of light nuclei?

- How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?

- How does nuclear matter respond to a fast moving color charge passing through it? How do quarks of different flavor dress themselves in nuclear matter to emerge as colorless hadrons? What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide them. The new experimental capabilities will be complemented by theoretical advances in LQCD calculations and in effective field theory approaches that are being developed explicitly for the gluon-dominated regime.

SCIENCE HIGHLIGHTS AT THE ELECTRON ION COLLIDER

The EIC, with high energy and high luminosity polarized beams, will unite and extend the scientific programs at CEBAF and RHIC in dramatic and fundamentally important ways, as illustrated in the following subsections by highlights of relevant theoretical calculations and simulations under realistic experimental conditions.

The Proton as a Laboratory for QCD

How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?

How Does the Proton Get Its Spin?

The decomposition of the proton's overall intrinsic spin into quark and gluon contributions remains a fascinating open question (see Sidebar 2.6). State-of-the-art QCD analyses of recent measurements at RHIC have shown that individual gluons that carry more than a few percent of a proton's momentum have a preference to align their own intrinsic spins along that of the proton's overall spin, thereby accounting for approximately

30–40% of the total. This contribution is similar to that from quarks and antiquarks. But even with anticipated further polarized proton collision runs, RHIC does not have the kinematic reach to meaningfully constrain the extrapolation of gluon spin preferences to the abundant lower-momentum gluons. Consequently, there is still a large uncertainty in the *net* contribution of gluons to the proton's spin, as reflected in the vertical extent of the blue band in Figure 2.14. Our knowledge of the gluon spin contribution, and to a smaller extent the net quark spin contribution, is limited by the limited range in parton momentum fraction (x) explored so far. The EIC would greatly increase the kinematic coverage in x and resolving power Q^2 for polarized deep inelastic scattering experiments, as shown in Figure 2.15. By probing the abundant lower-momentum gluons and sea quarks, EIC experiments will reduce the spin contribution uncertainties dramatically, as shown by red and yellow bands in Figure 2.14, providing a much clearer picture of how the proton's spin emerges from QCD.

Motion of Quarks and Gluons in a Proton
In addition to contributions to the overall proton spin from preferential spin orientations of quarks and gluons, there can be contributions from the orbital motion of quarks and gluons within the proton (see Sidebar 2.6). Such orbital contributions can be probed by orienting the spin of the beam protons perpendicular to their direction of motion and then looking for preferences for the partons inside to move toward one side or the other (see Figure 2.16). Such transverse motional preferences would be revealed precisely by EIC measurements, where one detects the scattered electron in coincidence with an emitted hadron emerging near the direction of the struck parton. For example, the contours in Figure 2.16 illustrate how such measurements could reveal a preference for up sea quarks to move toward the right within a proton that is itself moving out of the page at nearly light speed, with its spin pointing upward. Such unprecedented images illuminate correlations among partons that help to produce such emergent properties as the proton's spin. These images are simply unattainable without the polarized electron and proton beams and the high collision rates of the EIC.
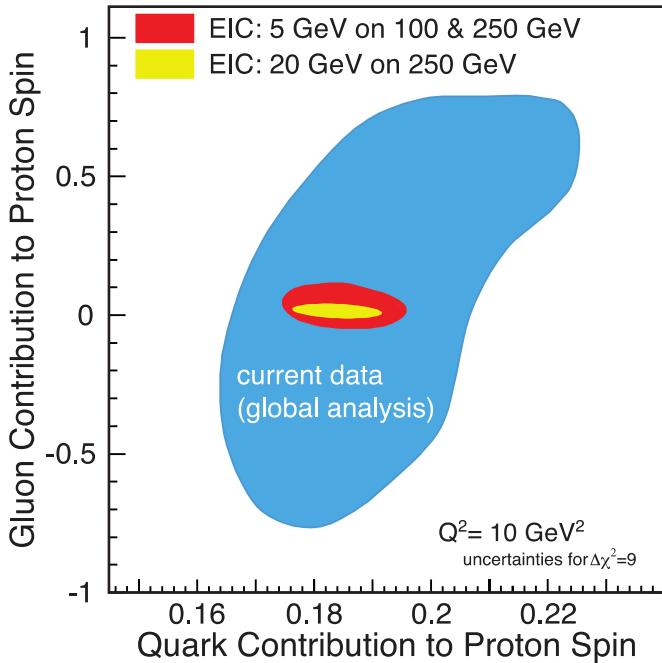
Figure 2.14: *The projected reduction in the uncertainties of the net gluon and net quark spin contributions to the proton's spin for EIC electron energies of 5 (red) and 20 (yellow) GeV.*

Figure 2.15: *The increased coverage (colored bands) over existing experiments (point symbols) that EIC polarized electron-proton collisions will provide in parton momentum fraction and resolving power.*
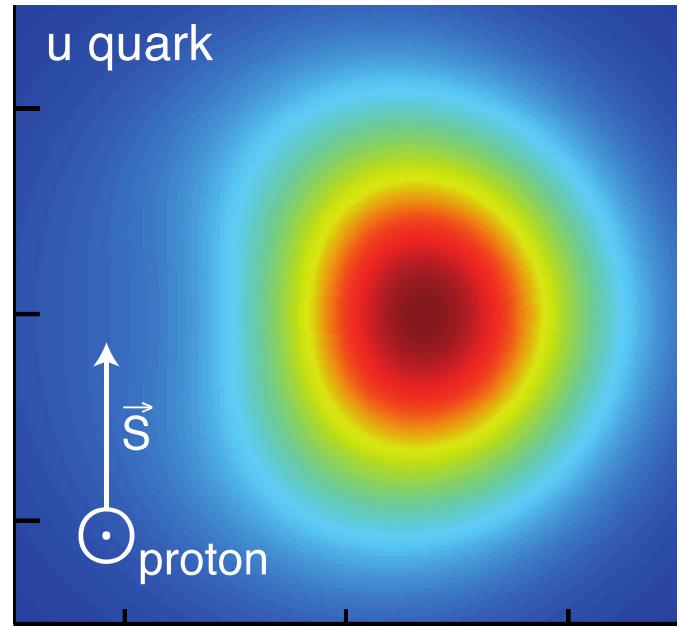
Figure 2.16: *A simulation based on projected EIC data of the transverse motion preferences of an up sea quark within a proton moving out of the page, with its spin pointing upward. The color code indicates the probability of finding the up quarks.*

Tomographic Images of the Proton

Deep inelastic scattering (DIS) experiments carried out at EIC collision rates will provide for the first time 3D images of gluons in the proton's internal landscape. Of particular interest are exclusive measurements, where one detects an outgoing meson in coincidence with the scattered electron with sufficient resolution to confirm that the proton has been left intact by the scattering process. For example, the detection of exclusive J/ψ meson production would provide unprecedented maps (Figure 2.17) showing how the gluons are distributed in space within a plane perpendicular to the parent proton's motion. These particular maps encode vital information, inaccessible without the EIC, on the amount of proton spin associated with the gluons' orbital motion.

Proton Spin at the EIC and Lattice QCD

The ability of LQCD calculations to reproduce many features of the hadron spectrum is a testimony to striking recent advances in our treatment of quark and gluon interactions from first principles. An important recent breakthrough in LQCD methodology now provides the promise of precision future comparisons of theory

with such detailed EIC measurements of proton spin structure as the images and distributions in Figures 2.16 and 2.17. Such comparisons will not only bring deep insight into the origin of the spin but will also shed light on the role the abundant gluons play in generating the proton's mass and confining quarks and gluons inside the proton.
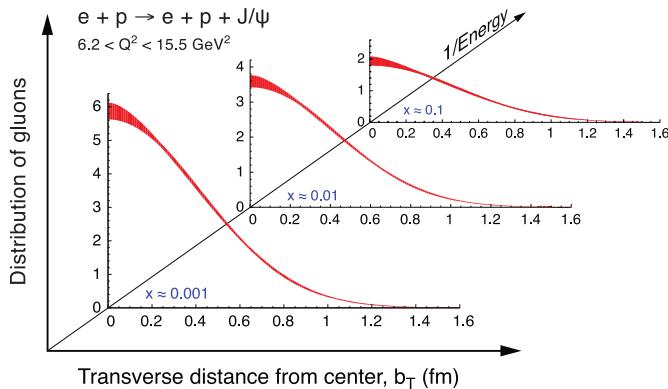
Figure 2.17: *Projected measurement precision for gluon distributions in transverse space inside a proton, obtained from exclusive J/ψ production at the EIC. Projections are shown for three different bins in the fraction of the proton's momentum carried by the gluons.*

Nuclei as a Laboratory for Emergent QCD Phenomena

How do gluons and sea quarks contribute to the nucleon-nucleon force, as manifested in the internal landscape of light nuclei?

The ability of the EIC to collide electrons with nuclei, from light to heavy and at varying energies, presents us with new and exciting ways to study and understand nuclear matter. The use of light nuclei with 2 to 12 nucleons, whose nuclear structure is experimentally well studied and well described by existing models, will allow us to *study* the nucleon-nucleon force at short distances but from the point of view of quarks and gluons. The recently discovered intriguing correlation between the quark motion inside the nucleus and the nucleon-nucleon force at short distance would be further elucidated by such studies at the EIC. Detection of spectators (those nuclear fragments that do not participate in the DIS process) from a nucleus can identify the active nucleon and study the nuclear binding effects and what role the partons play in them.

QCD Matter at Extreme Gluon Density

What happens to the gluon density in nuclei at high energy? Does it saturate, giving rise to a gluonic matter component of universal properties in all nuclei, even the proton? How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?

When fast-moving hadrons are probed at high energy, the low-momentum gluons contained in their wave functions become experimentally accessible (see Sidebar 2.7). By colliding electrons with heavy nuclei moving at near light speed, the EIC will provide access to an uncharted regime of all nuclear matter, where abundant gluons saturate in density and dominate its behavior. This regime, falling below the colored surface in Figure 2.18, is accessible with *heavy-ion* beams at the EIC, while much higher collision energies would be required to reach it in electron-proton collisions. The nuclear "oomph" experienced by a high-energy probe arises due to the coherent effects of gluons contributed by many nucleons. The probe no longer resolves individual quarks and gluons in the nucleus but rather samples strongly correlated matter. Gluons in the matter are as closely packed as possible; strong interactions, among the strongest in nature, ensure nuclei are stable against endless gluon proliferation.

This maximal close packing allowed by nature in collisions with certain energy establishes a resolution scale, denoted by Q_s, corresponding to sizes smaller than those of hadrons. The existence of this scale allows theorists to compute the properties of this remarkable matter, describing it as a color glass condensate (CGC). Previously, quarks and gluons were believed to form a nearly free gas of weakly interacting partons at very high resolution Q^2 and very strongly interacting confined matter on lower, hadron-size, resolution scales. As illustrated in Figure 2.18, gluon saturation suggests a new emergent regime in QCD where matter is not easily characterized as weakly or strongly interacting but has aspects of both.

A striking prediction of the CGC theory is that at very high energies, the properties of gluon matter in a nucleus are independent of its detailed structure; they can be expressed entirely in terms of ratios of Q_s and the resolution momentum scale Q of the external probe. Because of the claim that it controls the bulk of strong interaction phenomena at high energies, the study of this conjectured universal gluon matter is of high scientific interest and curiosity. At an EIC, theory predictions for the evolution of collective gluon dynamics toward this remarkable universal state can be explored and tested with precision by varying the energy, resolution, and atomic number for a large number of measurements. These will span, to the widest extent ever, the space

Sidebar 2.6: Nucleon Spin: So Simple and Yet So Complex

The simple fact that the proton carries spin 1/2, measured in units of Planck's famous constant, is exploited daily in thousands of magnetic resonance imaging images worldwide. Because the proton is a composite system, its spin is generated from its quark and gluon constituents. Physicists' evolving appreciation of how the spin might be generated, and of how much we have yet to understand about it, is an illustrative case study of how seemingly simple properties of visible matter emerge from complex QCD interactions.

Quarks are also spin 1/2 particles, and at any given moment an individual quark may spin in the same or the opposite direction of its proton host, respectively, making a positive or negative contribution to the total proton spin. Physicists originally expected the sum of

quark spins to account for most of the proton's spin but were quite surprised when experiments at CERN and other laboratories showed that the spins of all quarks and antiquarks combine to account for no more than about 30% of the total. This result has led nuclear scientists to address the more daunting challenges involved in measuring the other possible contributions to the spin illustrated in Figure 1. The gluons also have an intrinsic spin (1 unit) and might be "polarized" (i.e., might have a preferential orientation of their spins along or opposite the proton spin). And just as the earth orbits around the sun while simultaneously spinning about its own axis, the quarks and gluons in a proton could have orbital motion that would also contribute to the overall proton spin.
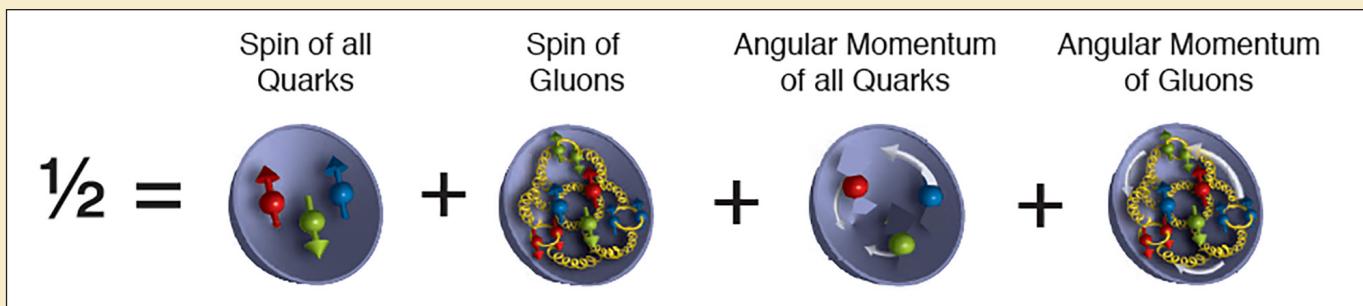
Figure 1: A schematic view of the proton and its potential spin contributions.

So how much of the spin comes from the spin of gluons? The first important constraints have come from recent measurements at RHIC, which provides the world's first and only polarized proton collider capability at high energy. There, the STAR and PHENIX experiments have used the polarized quarks in one proton as a scattering probe to reveal that the gluons in the other proton are indeed polarized. Just as critical has been the development of the theoretical framework to integrate the RHIC measurements into a global QCD analysis to constrain both quark and gluon spin preferences. Results of those analyses are shown in Figure 2.

The protons at RHIC move at nearly the speed of light, and each quark and gluon inside carries a fraction x of the proton's overall momentum. The widths of the colored bands in Figure 2 illustrate the uncertainties in the summed spin of all gluons that carry more than a fraction x_{min} of the proton's momentum, with the value of

x_{min} indicated on the horizontal axis. For each dataset, the uncertainties grow significantly at low x_{min} as the contributions have not been directly measured there.

In a significant breakthrough, the RHIC results to date (light blue band in Figure 2) indicate that the gluon spins do indeed have a non-negligible orientation preference for x above 5%. But they tell us very little about whether the much more abundant lower-momentum gluons may reinforce or counterbalance this preference. This leaves a large uncertainty in the total gluon spin contribution, indicated at the left edge of the plot, which can be reduced by analysis of anticipated RHIC polarized proton data (the darker blue band). However, this still would leave the overall uncertainty at a level that remains larger than the entire proton spin itself. Only an EIC (yellow band) can uniquely settle how much of the overall spin is contributed by the spins of quarks, antiquarks, and gluons combined.

If this summed spin contribution is not enough to account for the total, orbital angular momentum of quarks and/or gluons must come to the rescue. Here again, the EIC will provide a wealth of relevant data. Orbital angular momentum depends on the correlation between positions and momenta of the quarks and gluons, information contained within unprecedented three-dimensional images of the sea quark and gluon distributions that will become available with the EIC.

The quest to understand how the proton gets its spin has led us naturally to study the distributions of quarks and gluons—in space, in momentum, and in spin preference—from low to high resolution scales, providing important clues on the inner structure of the proton in terms of the dynamics of quarks and gluons. Experiments at RHIC, at the 12-GeV Upgraded CEBAF at Jefferson Lab, and the COMPASS experiment at CERN all provide some pieces of this puzzle. However, *only* a future EIC can fully reveal what makes up the proton spin.

Figure 2: *Constraints on the spin sum of gluons carrying more than a fraction x_{min} of the proton's momentum. The width of each band represents the range of values allowed by existing and projected DIS and RHIC spin data.*

illustrated in Figure 2.18 to confirm the existence of and, hence, extract the properties of saturated gluon matter.

Evidence regarding the saturation regime can be obtained at an early stage of EIC operations by measuring diffractive cross sections. In these measurements, the nucleus remains intact despite the enormous energy of its collision with the electron. When combined with the total DIS cross-section (in electron+proton and electron+nucleus collisions), diffractive measurements at the EIC, as shown in Figure 2.19, will be able to distinguish between CGC models containing the saturation window shown in Figure 2.18 and those that do not. The EIC will, therefore, provide the first unambiguous evidence for whether the transition from a dilute gas of quarks and gluons to the closely packed regime of proliferated gluons has been achieved.

Further, the wavelike features of quantum mechanics can be exploited in such measurements to extract essential information on where the saturated gluons are localized in nuclei. Visualize the electron beam exchanging a photon with the nucleus and that this photon can fluctuate into a quark-antiquark pair, which acts as a microscope sensitive to the gluons in

the nucleus. Because of the wave-particle duality of quantum mechanics, the quark-antiquark system can scatter as a wave off gluon locations in the nucleus, producing diffraction patterns analogous to those produced by light waves. Thus, just as light waves inform us about spatial distributions in a diffraction grating, the reconstituted quark-antiquark system (for example, a phi-meson) leaving the nucleus intact provides fundamental information on where gluons are localized. Such measurements of exclusive production of the phi or other mesons in electron-nucleus collisions are unique to an EIC and are an extraordinarily powerful tool, providing spatial information to complement the energy and resolution landscape in Figure 2.18, both above and below the saturation surface.

Relevance of EIC Measurements to LHC/RHIC Results
Besides its fundamental interest, information from the EIC on the location, fluctuations, and correlations within saturated gluon matter in the nuclear wave functions will provide a unique perspective—complementary to what can be learned from heavy- ion collisions—on two aspects of results from RHIC and LHC. These aspects are how the perfect liquid QGP is formed so rapidly, and how spatial inhomogeneities in the colliding gluon fields

are imprinted on the QGP and then transported to the final state by the perfect liquid. With regard to the former, recent experiments at RHIC and LHC provide surprising evidence of collective behavior in rare high multiplicity configurations generated even when light ions collide with heavy ions. It is possible that this evidence reflects collective behavior that was already present in the initial saturated gluon states of the colliding nuclei, in which case analogous DIS measurements at the EIC should show similar features. Alternatively, the RHIC and LHC evidence might indicate the formation of small QGP droplets even in light-ion-heavy-ion collisions, in which case EIC experiments should not show similar effects.

With regard to the second aspect mentioned above, highly precise data are becoming available from the RHIC and LHC heavy-ion collisions on anisotropic patterns in particle emission that reflect early QGP matter density distortions of progressively more complex geometry. Comparisons of these anisotropies to hydrodynamic models can be used to extract the transport properties of the QGP with precision and to constrain the shape distributions of the initial state. The complementary constraints on the initial state extracted from EIC measurements will help facilitate the high-precision extraction of the viscosity and other transport coefficients in the QGP liquid.

Figure 2.19: The ratio of diffractive over total cross section for DIS on a gold nucleus normalized to DIS on a proton, for different values of the mass-squared of hadrons produced in the collisions, predicted with (red curve) and without (blue curve) gluon saturation. The projected experimental uncertainties are smaller than the plotted points while the range of each model's prediction (shaded bands on the left side) is smaller than the difference caused by saturation.

Figure 2.18: The schematic QCD landscape in probe resolving power (increasing upward) vs. energy (increasing toward the right), as a function of the atomic number of the nucleus probed. Electron collisions with heavy nuclei at the EIC will map the predicted saturation surface (colored surface) with the CGC region below that surface. Spatial distributions extracted from exclusive reactions (see text) will help demarcate the CGC region from the confinement regime.

Formation of Hadrons and Energy Loss

How does nuclear matter respond to a fast moving color charge passing through it? How do quarks of different flavor dress themselves in nuclear matter to emerge as colorless hadrons? What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?

The emergence of hadrons from quarks and gluons is at the heart of the phenomenon of color confinement in QCD. The dynamical interactions of energetic partons passing through nuclei or QGP provide unique analyzers, probing the poorly understood evolution from colored partons to color neutral hadrons. As envisioned in Figure 2.20, a nucleus in a collision at the EIC would provide a femtometer size "detector" to monitor the evolution from partons to hadrons.

For example, EIC experiments will measure the difference between producing light π mesons (containing up and down quarks) and heavy D^0 mesons (containing a charm quark) in both electron+proton and electron+nucleus collisions. These measurements will provide critical information on the response of cold

nuclear matter to fast moving quarks with different masses (compare π to D^0 production) and lengths of color neutralization (small versus large nucleus size). The dramatic difference between the production of a π and D^0 meson, shown in Figure 2.21, caused by the predicted mass-dependence of the quark energy loss, would be easily discernible at the EIC. The difference between model I and model II for light quarks reflects the current limits of our knowledge on the formation of a pion from a colored quark, commonly known as hadronization. Through the study of hadronization in DIS, the EIC presents us with the tools to dial with precision the formation of light and heavy hadrons inside or outside the nuclear medium. This will offer a fresh window into how quarks and gluons are confined in nuclear matter and in vacuum. The precision data that will become available at the EIC on the energy loss of quarks and gluons in cold nuclear matter will provide an important benchmark complementing similar studies of the response of the hot QGP to fast moving quarks.

There is unambiguous evidence that they both play surprisingly important roles for defining the structure of nuclear matter around us. Their quantitative study and understanding require a novel sophisticated tool, the EIC. The key machine parameters the EIC should have to address the compelling questions described above are well established.

- Polarized (~70%) electrons, protons, and light nuclei

- Ion beams from deuterons to the heaviest stable nuclei

- Variable center of mass energies ~20–100 GeV, upgradable to ~140 GeV

- High collision luminosity ~10^{33-34} cm^{-2}sec^{-1}

- Possibly have more than one interaction region

Figure 2.20: A schematic illustrating the interaction of a struck parton moving through cold nuclear matter, with hadrons formed either outside (top) or inside (bottom) the nucleus.
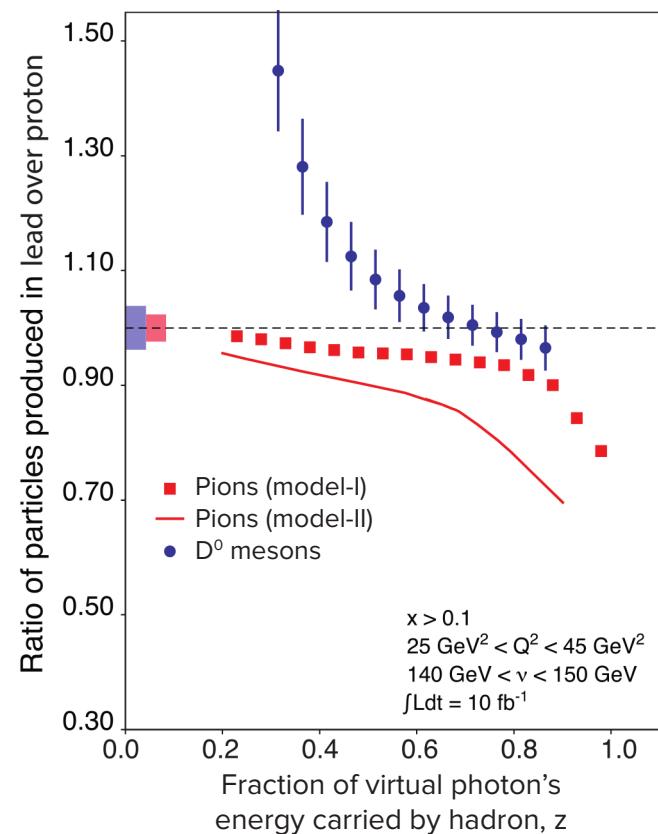
Figure 2.21: Model predictions of the ratio of cross sections for producing a pion (light quarks, red) or a D^0 meson (heavy quarks, blue) in electron+Pb to electron+proton DIS collisions plotted as a function of z, the fraction of the virtual photon's momentum carried by the produced hadron. Projected measurement uncertainties are sufficient to clearly distinguish the effects of nuclear passage as a function of both momentum and energy transfer with the exchanged photon and struck quark mass.

EIC: Why Now and Why in the U.S.?

Our view of the structure of atomic nuclei and the nucleons they contain has made quite a transformation in the last few decades. The most common picture found in textbooks shows a simple three-valence quark structure of the nucleon, yet we now know that the inside of the nucleon is rather a complex many-body system with a large number of gluons and sea quarks.

The realization of the EIC will require the same core expertise that led to the versatility of the polarized proton and heavy-ion beams at RHIC, at Brookhaven National Laboratory, and the unique polarized electron beam properties of CEBAF at Jefferson Lab. This expertise at the U.S. laboratories will be crucial in meeting the technical challenges to realize the versatile range of kinematics, the broad range in ion beam species, and the high luminosity and beam polarization at the EIC: all critical to addressing the most central questions for QCD matter, while at the same time maintaining U.S. leadership in the fields of nuclear and accelerator science.

A set of compelling physics questions related to the role of gluons and sea quarks in nuclear matter has been formulated, and a corresponding set of measurements at the EIC identified. A powerful formalism that connects those measurements to the QCD structure of hadrons and nuclei has been developed. We have articulated ways in which the EIC would provide unique and precise information on emergent dynamics of sea quarks and gluons in the structure of nuclear matter. However, if history of emergent phenomena in other subfields of physics is any guide, surprises and unanticipated novel directions of study can be expected with high probability. This is especially likely for the EIC since much of the gluon- and sea- quark dominated region it will explore in nuclei and polarized protons is *terra incognita*.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier." In 2013 the NSAC Subcommittee report on Future Scientific Facilities declared an EIC to be "absolutely essential in its ability to contribute to the world-leading science in the next decade." The strong and worldwide interest in a U.S.-based EIC has been rapidly growing. Countries such as China, France, India, Italy, and Japan have expressed strong interest in collaborating on the physics, the detector, and the accelerator technologies. Now is the time to realize the EIC in the U.S.

Sidebar 2.7: An Evolving Picture of Nuclei

The nucleus is a tiny object, about 100,000 times smaller than a typical atom. A central goal of nuclear physics, since the birth of the subject, has been to image the internal landscape of nuclei in order to understand how they are assembled and how they interact. The strong interaction that binds the nucleus leads to a fascinating, multi-layered internal picture, as suggested by the five views shown in the figure.

The most precise information physicists have about the internal structure comes from scattering electrons, which interact with the nucleus by exchanging a virtual photon. The photon can transfer momentum and energy from the electron to the nucleus, and the layers of structure exposed change as one varies these quantities. At very low momentum transfer (see figure, frame a), the photon's resolving power is insufficient to see any details; it just senses the nucleus' overall electric charge and magnetic moment (which is zero for many nuclei). With increasing electron energy and momentum transfer, one begins (frame b) to resolve the spatial distribution of electric charge and magnetization inside the nucleus and senses how the protons inside are distributed. Robert Hofstadter won the 1961 Nobel Prize for using

this technique to reveal that the proton itself also had a charge distribution.
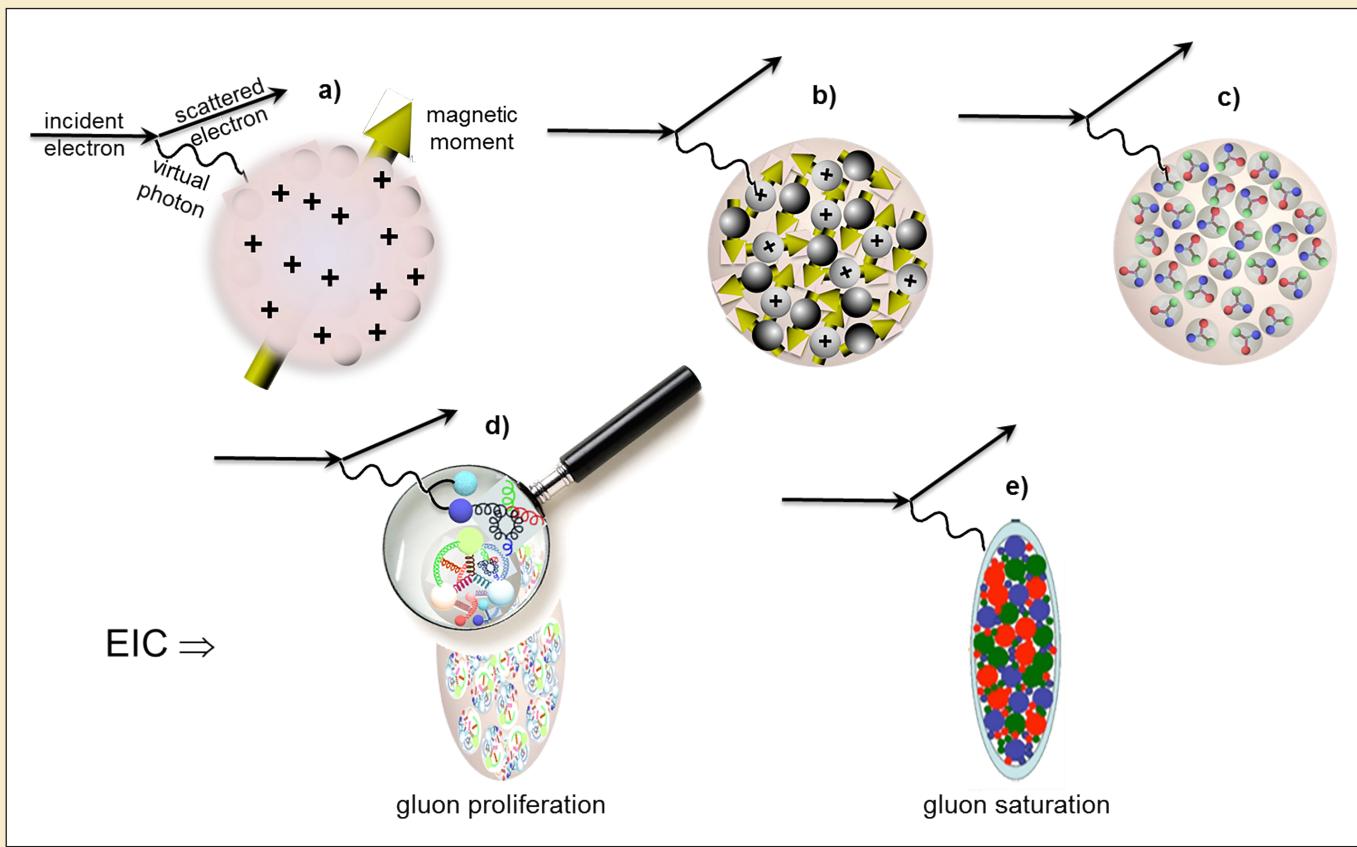
With sufficient electron beam energy, the virtual photon can transfer enough energy and momentum to probe inside individual nucleons (frame c). Friedman, Kendall, and Taylor won the 1990 Nobel Prize for using this DIS process to demonstrate that virtual photons interact with pointlike fractionally charged particles inside the nucleon (i.e., with quarks). Currently, CEBAF uses DIS to study the distribution of valence quarks—the quarks that define the charge and magnetic moment—in individual nucleons and in nuclei.

If one holds the photon's resolving power in the same range studied at CEBAF, but at dramatically increased electron-nucleus collision energy, one exposes nucleon constituents that each carry tiny fractions of the overall nuclear momentum. This is the basically unexplored region dominated by the proliferation (frame d) and eventual saturation (frame e) of gluons that is the focus of an EIC. Even though each gluon (represented by colored springs in frame d) carries no electric charge or magnetism itself, it can interact with a photon that

splits into a quark and antiquark, each of which has both electric and color charge. If, for example, the quark and anti-quark recombine after the scattering to form a phi-meson, which one detects in coincidence with the scattered electron to reveal that the nucleus has been left intact, one can infer the spatial distribution of gluons in the nucleus—unprecedented information extending the work of Friedman, Kendall, and Taylor to a new layer of internal structure.

At sufficiently low momentum fraction, the density of gluons inside a nucleus must saturate, as in frame (e), in order to avoid violating fundamental physical principles. This can occur because at high density the probability for two gluons to recombine into one counterbalances the probability for one gluon to split into two. Before

saturation is reached, an electron encountering a nucleus moving toward it near light speed sees a relativistically contracted object as in frame (d), with much higher gluon density than it would if colliding with a single proton. In fact, to attain comparable gluon densities, one would have to study electron-proton collisions at energies two orders of magnitude higher than in electron collisions with heavy nuclei. This is why the ion beams are so important in the EIC. They provide early access, allowing us to image nuclei as strongly correlated gluon systems with universal properties. This picture of nuclei—indeed, of all hadrons—determines their interactions at very high energies, whether in a terrestrial collider facility such as RHIC or LHC or in the highest energy radiation from cosmic sources. It is the ultimate picture of nuclei at their deepest level.

Schematic illustration of the evolving landscape in a nucleus as we alter the resolving power and energy of the electron scattering process used to probe it.

3. Nuclear Structure and Reactions

The atomic nucleus is at the core of all visible matter and comprises 99.9 % of its mass. Its relevance spans dimensions from 10^{-15} m (the proton radius) to objects as large as stars and covers the evolutionary history of the universe from fractions of a second after the Big Bang to today, 13.8 billion years later. The subfield of nuclear structure and reactions strives to measure, explain, and use nuclei to meet society's scientific interests and needs. This research addresses the underlying nature of atomic nuclei and the limits to their existence. It also aims to describe dynamical processes such as nuclear reactions and fission. The ultimate goal is to develop a predictive understanding of nuclei and their interactions grounded in fundamental QCD and electroweak theory; furthermore, this understanding must be based on experimental data from a wide variety of nuclei. Part of the challenge is to understand which nuclei are going to be the most interesting or important in realizing this goal and then to make them in the laboratory. Today, we have identified some of the key nuclei, but we do not yet have the means to make them.

Since the last Long Range Plan in 2007, we have considerably increased our understanding of the nucleus and its role in the universe. But answers to the overarching questions that drive the field require still deeper understanding of atomic nuclei, both theoretically and experimentally. The breadth of the research questions requires complementary approaches with a variety of tools and techniques.

As reaffirmed by the 2013 National Research Council report, *Nuclear Physics, Exploring the Heart of Matter,* the path to understanding the nucleus requires the timely completion of FRIB and its effective operation. Unprecedented access to a vast new array of nuclei will result in scientific breakthroughs and major advances in our understanding of nuclei and their role in the cosmos and will open new avenues in cross-disciplinary contributions to basic sciences, national security, and other societal applications. In preparation for the FRIB era, much work remains to be done at existing facilities: the nation's flagship NSF nuclear science facility NSCL; DOE's facilities, ATLAS and Jefferson Lab, which have world-unique capabilities; and the university labs. Even after FRIB is operational, the program will need to be complemented with cutting-edge research projects with stable beams at ATLAS and at university laboratories. These are, and will remain, critical for specific programs that require stable or selected rare-isotope beams or that require more experimental running time than will be easily available at FRIB. With powerful experimental facilities and computational resources in nuclear theory, the field has a clear path to achieve its overall scientific goals.

THE ORIGIN AND EVOLUTION OF NUCLEI

Where do nuclei and elements come from? What combinations of neutrons and protons can form a bound atomic nucleus? The answers have important consequences for nuclear structure and astrophysics. Figure 3.1 shows a map of the nuclear landscape. Only 288 isotopes (black squares) are stable on the time scale of the solar system. Moving away from the region of stable isotopes by adding nucleons (either neutrons or protons), one enters the regime of short-lived radioactive nuclei. Nuclear existence ends at the "drip lines," where the last nucleon is no longer bound to the others and literally drips off. Although the proton drip line has been reached for many elements up to Z=83, remarkably, the neutron drip line is known only up to oxygen (Z=8). The superheavy nucleus with Z=118, A=294 marks the current upper limit of nuclear charge and mass. Those borders define the currently known nuclear territory. Today, about 3000 isotopes are known to exist (green squares), less than half the number predicted by current nuclear theory.

The quest for the limits of nuclear binding is closely connected to the roadmap toward a comprehensive theory of all nuclei. It is also crucial to an understanding of the origin of elements in the universe since the astrophysical processes that generate many heavy elements occur relatively close to the drip lines in what is now nuclear *terra incognita* (see Chapter 4). To build a comprehensive model that describes quantitatively and predictably the nuclear quantum system, experiment and nuclear theory will have to work in concert. New insights from experiments on rare isotopes previously not available will guide theoretical developments.
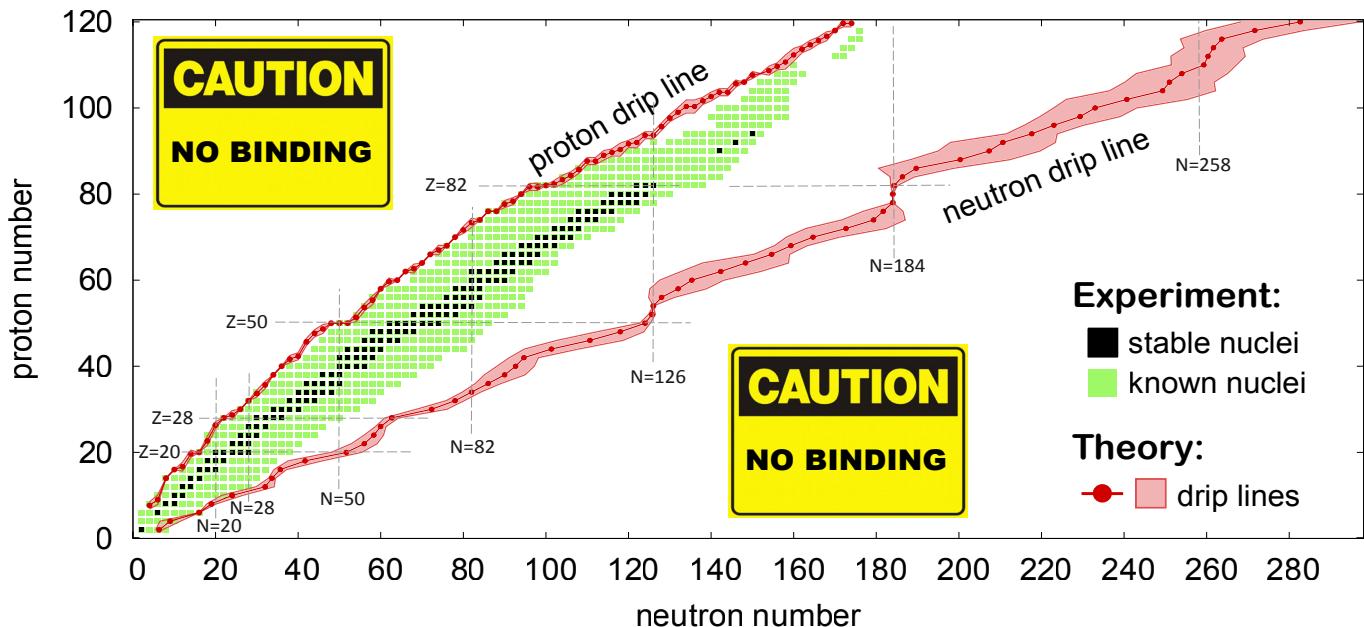
Figure 3.1: *Nuclear landscape. Map of bound nuclei as a function of Z and N. Mean drip lines, where the nuclear binding ends, and their uncertainties (red) were obtained by averaging the results of different theoretical models.*

May the Strong Force Be with You

A long-standing effort is to understand how QCD in the low-energy regime manifests itself in nuclear phenomena. We know, for example, that the nucleon-nucleon interaction, which is governed by the quark and gluon dynamics at short distances, can be viewed at large distances in terms of pion exchange. Bridging these two distance scales, connecting hadrons with light nuclei, refines our insights into the structure of nuclear forces, a great prospect. LQCD calculations will be particularly useful for those parts of the nuclear force that are difficult to address experimentally, such as the forces encountered by three nucleons approaching each other closely (three-nucleon forces). Lattice developments already include computations of nucleon-nucleon scattering and the binding energies and magnetic moments of light nuclei; other recent theoretical advances have provided us with a systematic approach to the nuclear force. Experimentally, by knocking out nucleons from the nucleus using high-energy electromagnetic probes, researchers have investigated the behavior of nucleonic pairs in nuclei at very short distances, as presented in Chapter 2.

Quantitative modeling requires high-quality input. To increase the predictive capability of nuclear theory, modern methodologies have been developed to optimize nuclear forces to few-body systems and light nuclei. Another important goal is to develop an accurate

interaction effective in nuclei and rooted in *ab-initio* theory. Properties of nuclear forces that depend on neutron-to-proton imbalance are not well constrained by the existing data. FRIB, with its extended reach in the *N/Z* ratio, will dramatically improve the situation.

Life in the Nuclear Borderlands
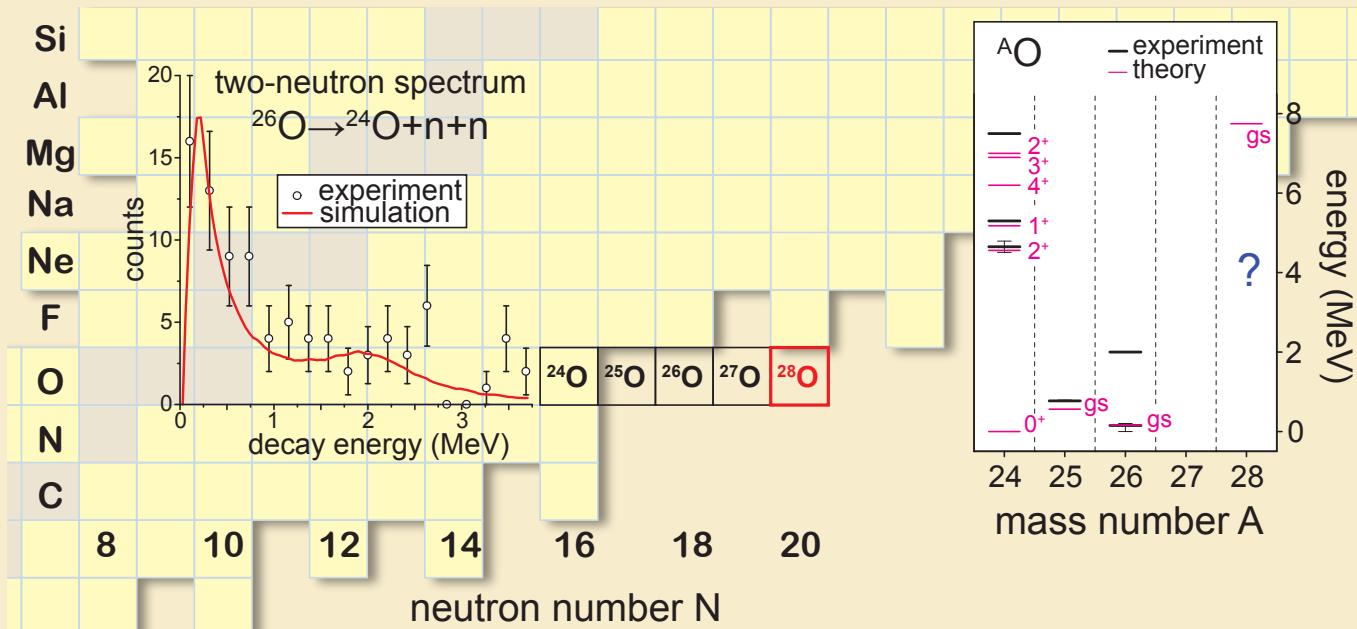
The territory of neutron-rich nuclei is the most fertile ground for research in nuclear structure. One of the paradigms of nuclear structure is the shell model of the atomic nucleus, in which a common force generated by all other nucleons governs the motion of each neutron or proton. Thanks to this common force, nucleonic orbits bunch together in energy, thereby forming "shells," and nuclei having filled nucleonic shells are exceptionally well bound. The numbers of nucleons needed to fill each successive shell are called the magic numbers: the traditional ones are 2, 8, 20, 28, 50, 82, and 126; until recently they have been assumed to be immutable. However, a dramatic series of discoveries with current rare isotope research on the proton-magic oxygen (Z=8), calcium (Z=20), nickel (Z=28), and tin (Z=50) isotopes have shaken that assumption. For example, spectroscopic studies of neutron-rich oxygen isotopes (Sidebar 3.1) provided substantive evidence for new magic numbers at N=14 and 16, an outcome that explains the surprising location of the drip line for oxygen.

Sidebar 3.1: Beyond the Limits of Nuclear Stability

The secrets of the nuclear force are encoded in the heavy oxygen isotopes. The stable ^{16}O isotope with Z=8 protons and N=8 neutrons is doubly magic: with its enhanced stability due to filled neutron and proton "shells," it is a poster child for the traditional nuclear shell model. However, as we move away from the stable oxygen isotopes to those with extreme neutron-to-proton ratios, we find that textbook knowledge needs substantial revision. Measurements of the neutron-rich isotopes ^{22}O and ^{24}O suggest the presence of new magic numbers at N=14 and 16. Also, although the chain of bound oxygen isotopes appears to terminate at ^{24}O, it does not mean that the life of oxygens ends there. Novel experimental techniques have provided insights into properties of the neutron-unbound ^{25}O and ^{26}O. In particular, the nucleus ^{26}O behaves in a most peculiar way as it decays to ^{24}O by spitting out two neutrons. The figure shows the two-neutron decay spectrum to be dominated by a low-energy narrow peak, whose measured half-life could be as large as 10^{-12} s. While incredibly short on the human timescale, this lifetime is more than 10^{10} times longer than the typical timescale of nuclear motion; hence, the fleeting ^{26}O can, indeed, be considered a nucleus and its decay, a new form of radioactivity! If ^{26}O is a viable nucleus, then what about ^{28}O, a nucleus containing two more neutrons? Its ground state is of great interest since, according to the textbooks, this rare isotope with N=20 should be doubly magic. But is it?

The unique data on bound and unbound states of the oxygen isotopes have been used to benchmark ab-$initio$ models of nuclei that employ two- and three-nucleon forces, resulting in the development of a vastly improved theoretical formalism. As shown in the figure, the current state-of-the-art models are capable of explaining observations beyond the limits of nuclear stability. According to these models, the intricate behavior of the oxygen chain can be partly attributed to poorly understood three-nucleon forces. The planned experimental searches for ^{28}O and more detailed studies of two-neutron radioactivity in ^{26}O will provide crucial data for refining nuclear models at the limits of nuclear existence.

Tests of nuclear paradigms have been carried out in light and heavy nuclei. For instance, studies of neutron-rich nuclei have led to the identification of the weakly unbound nucleus ^{26}O as a possible candidate for the elusive phenomenon of two-neutron radioactivity (see Sidebar 3.1), which will ultimately provide a sensitive probe of neutron pairing. The masses of neutron-rich calcium isotopes have also been precisely measured as far as ^{54}Ca, which contains six more neutrons than the heaviest stable calcium isotope, and the first spectroscopic study has been completed for ^{54}Ca and ^{60}Ti. These measurements allow us to extrapolate towards ^{60}Ca, the N=40 isotope that is key to the location of the neutron drip line in that region of the nuclear chart. However, the spectroscopy of ^{60}Ca will only be possible at FRIB with the Gamma-Ray Energy Tracking Array (GRETA), a high-efficiency, large-acceptance detector that can track γ-rays, and HRS, a high-rigidity recoil separator that can handle the highest energy neutron-rich beams. In a region of heavier nuclei, a series of pioneering experiments have exploited single-nucleon transfer reactions and Coulomb excitation with neutron-rich rare-isotope beams of tin to explore excited states in and around the doubly-magic ^{132}Sn. Augmenting this information are Penning-trap mass measurements of neutron-rich nuclides, including ^{132}Sn itself and many others even farther from stability.

Further progress in this area requires measurements of key isotopic chains, such as those of calcium and nickel that encompass multiple magic numbers. With FRIB and its suite of unique instrumentation, these chains will be accessible from proton drip line to neutron drip line, permitting the study of the N/Z dependence of the nuclear force and continuum effects over broad ranges. Such investigations will allow us to explore new paradigms of nuclear structure in the domain where many-body correlations, rather than the nuclear mean-field, dominate. Single- and even multiple-neutron emission are expected to characterize nuclei at the neutron drip line, while beta-delayed-neutron decay is prevalent among neutron-excess nuclei before the drip line is reached. Both forms of radioactivity only occur among nuclei far from stability.

The territory at and beyond the proton drip line offers unique opportunities to study other exotic nuclear decays and correlations, such as ground-state one- and two-proton decay, a class of radioactivity that exists nowhere else but that provides unique insight into correlation effects. The astrophysically important one-proton emitter, ^{69}Br, has already been studied, and the two-proton decay of the doubly-magic ^{48}Ni nucleus has been observed for the first time.

Theory of Nuclei: To Explain, Predict, and Use

We now recognize the need for a significant revision of textbook descriptions of the motion of protons and neutrons inside the nucleus. The drivers of the modified shell structure can be attributed to small but crucial ingredients of the nuclear force that have not been quantified before. Experimental data have led to the most significant advance in our understanding of the nuclear many-body problem in decades, where poorly known forces involving three nucleons and effects due to unbound states are all in a sensitive interplay. Much progress has been achieved through computational partnerships between nuclear theorists, computer scientists, and applied mathematicians. In recent years, we have been witnessing the revolutionary development of complementary *ab-initio* methods based on realistic nuclear forces that have been applied to critical problems in light nuclei, including the structure of the Hoyle state in ^{12}C, which gives rise in nucleosynthesis to the light elements that enable life; the long half-life of ^{14}C, which enables carbon dating; and the interaction between neutrinos and nuclei.

Insights from *ab-initio* computations have also offered an improved understanding of binding energies and excited states of heavier nuclei, such as key neutron-rich isotopes of oxygen and calcium, including unbound ^{25}O and weakly bound ^{54}Ca. In particular, the region around ^{54}Ca provides an excellent experimental venue to confront predictions using both *ab-initio* and nuclear density functional theory, the tool of choice for describing heavy complex nuclei. The application of high-performance computing has revolutionized theories of complex nuclei by both optimizing the input and carrying out advanced applications. Recent highlights include large scale surveys of global nuclear properties that enabled predictions of nucleonic drip lines with quantified uncertainties (see Figure 3.1), the elucidation of structure of superheavy nuclei, and quantitative modeling of fission and heavy-ion fusion reactions.

Another long term goal is to unify the fields of nuclear structure and reactions. This is already happening for light nuclei where few-body approaches, *ab-initio* methods, and continuum shell models can be applied.

Examples are key reactions involving composite projectiles, such as d + ^{7}Li ➜ ^{8}Li + p, n + ^{6}Li ➜ ^{4}He + ^{3}H (important in fusion research), or ^{4}He + ^{3}He ➜ ^{7}Be + γ (relevant for the standard solar model). In the area of nuclear reactions involving more complex nuclei, good progress has been achieved in developing a microscopic reaction theory capable of reproducing experimental data and providing realistic extrapolations to neutron-rich systems.

Superheavy Nuclei and Atoms: A Tug of War of Forces
It was recognized long ago that, in spite of the huge electric repulsion between all those protons in the nucleus, the binding that comes from the strong force could tip the balance in favor of the existence of superheavy nuclei. However, precise calculations at the limits of mass and charge are difficult. Recent experimental progress in this field has come from the realization that new elements can be synthesized by using neutron-rich beams, such as ^{48}Ca, to bombard targets of very heavy elements such as berkelium (see Figure 3.2). In addition, ion trap measurements have effectively extended the region of precisely known masses up to elements 110 and 111. These important steps forward in heavy-element discovery have been matched by pioneering measurements of the decay chains originating from element 115, the first time information has been acquired on the excited states of superheavy elements. We now know that there is a gradual onset of increasing stability for isotopes with $Z \geq 111$ when moving towards N=184, the anticipated center of stability in superheavy nuclei (Figure 3.2). To find the most favorable conditions for getting there experimentally and for producing even heavier elements, extensive measurements with fusion reactions of different types have been carried out. One of the most significant results came from a study of highly excited states in ^{274}Hs produced in hot fusion reactions that revealed a high survival probability. ATLAS with upgraded intensity and FRIB with neutron-rich beams will inform us how to reach the expected region of long-lived superheavy nuclei.

The future is bright. Ongoing improvements in experimental capabilities, such as K X-ray detection and a gas catcher coupled with a mass-separator, will enable the first direct Z and A identification of superheavy elements with Z $\geq$ 114. One-atom-at-a-time chemistry studies will also expand into this region. Since atomic relativistic effects increase rapidly with atomic number, the superheavy region is expected to produce significant deviations from the organizational principles captured by the existing periodic table of the elements. Recently, by using individual atoms of copernicium (Z = 112) experiments have made it possible to place this element in group 12 of the periodic table, under mercury, cadmium, and zinc. More insights will undoubtedly follow (see Sidebar 9.4).

THE ORIGIN OF NUCLEAR PATTERNS
How are nuclei organized? Complex systems often display surprising simplicities; nuclei are no exception. The resulting emergent phenomena, such as the appearance of nucleonic shells, saturation, rotation, superfluidity, and phase transitions, naturally develop in diverse many-body systems independent of the details of the interactions between the constituent particles. This perspective, focused on a highly organized complex system exhibiting regular patterns and symmetries, is complementary to the microscopic view of a nucleus made from small building blocks.

Dancing in Unison
It is remarkable that a heavy nucleus consisting of hundreds of rapidly moving protons and neutrons can exhibit a regular behavior, reflecting collective properties of many nucleons operating together. Oftentimes, regularities in nuclei signal the appearance of many-body symmetries and associated emergent behavior. Linking highly successful symmetry-based descriptions, which are capable of describing vast amounts of data, to microscopic theory is an important quest. To this end, specific data on nuclei at the extremes of neutron-to-proton asymmetry and angular momentum are needed.

This area has seen excellent progress since 2007. Excited-state lifetime measurements were used to show that proton and neutron shape deformations are similar in extremely neutron-rich $^{16\text{-}20}$C isotopes. A remarkable variation in collectivity, with a rapid shape change from spherical to deformed and the appearance of coexisting states, has been found in the N=40 isotones of Ni, Fe, and Cr. Gamma-ray spectroscopy of ^{158}Er has revealed collective rotation at record ultra-high angular momenta approaching 80 $\hbar$. In the near future, attempts will be made to reach the limit of angular momentum, where nuclei
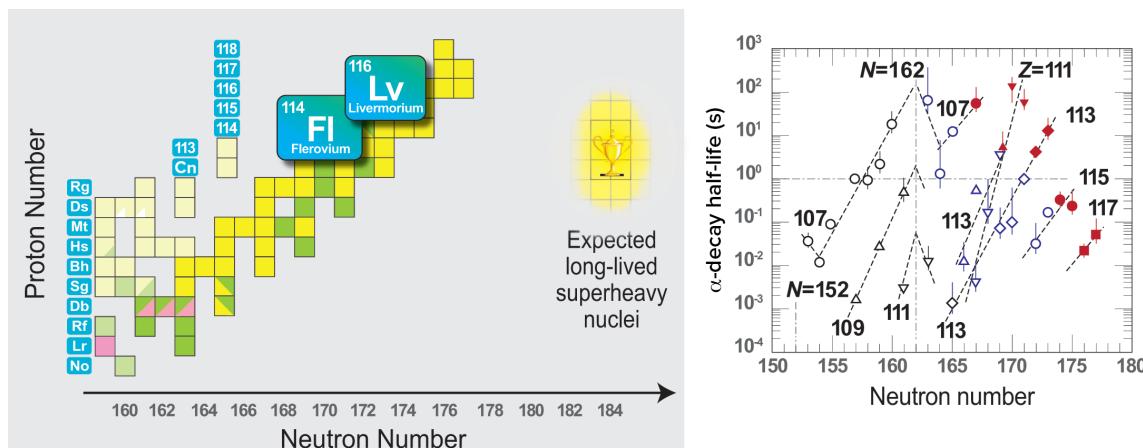
Figure 3.2: *Left: Upper end of the chart of nuclides showing the isotopes produced and studied during the last decade using the neutron-rich beam of ⁴⁸Ca. A new chemical element with Z=117 has been discovered and experimentally confirmed; two other previously discovered elements with Z=113 and 115 have been confirmed; and two more have been officially named, joining the periodic table as flerovium (Z=114) and livermorium (Z=116). The expected region of long-lived superheavy nuclei around N=184, Z=112 is marked. Right: The dependence of α-decay half-life on neutron number of odd-Z super heavy nuclei. The recently discovered nuclei (blue and red symbols) are trending to longer half-lives as N increases.*

spin so fast that they split, and the fragments fly apart. An important future challenge is the region of N=126 nuclei below lead in atomic number. This unexplored heavy mass region has an impact on the production of heavy nuclei in the astrophysical r-process and will test our understanding of the evolution of shell structure.

With the world-class GRETINA γ-ray spectrometer and equipment associated with it, in-beam nuclear spectroscopy will increase its reach to nuclei with more excess neutrons. This advance towards the neutron drip line will lay important groundwork for the much greater advances anticipated with GRETINA's successor GRETA. Furthermore, a new expanse of nuclear territory with $Z \gtrsim N$, at and beyond the proton drip line, will become accessible up to ¹⁰⁰Sn. The properties of these nuclei and reactions with them can be used to study new phenomena such as super-fast Gamow-Teller beta decays (especially around ¹⁰⁰Sn), the role of proton-neutron pairing, and alpha clustering at the nuclear surface.

Neutron-Rich Matter in the Cosmos and on Earth

Protons and neutrons in neutron-rich nuclei experience a different environment than their cousins in stable nuclei. In heavier neutron-rich nuclei, the excess of neutrons collects at the nuclear surface creating a "skin," a region of weakly-bound neutron matter that is our best laboratory access to the diluted matter existing in

the crusts of neutron stars (see Sidebar 3.2). To probe the neutron skin experimentally in a model-independent way is, however, extremely difficult. Parity-violating electron scattering provides a solution to this problem, and an experiment was performed at JLab that has demonstrated the feasibility of this method. Future experiments will study the neutron skin thickness of ²⁰⁸Pb and ⁴⁸Ca. One of the main science drivers of FRIB is the study of neutron skins three or four times thicker than is currently accessible. According to theory, weak binding does impact the nature of superfluidity in the neutron skins. Here the exciting prospect is to explore neutron pairing in the most neutron-rich matter available in any terrestrial laboratory by means of transfer reactions that add or remove two neutrons from nuclei with extreme neutron skins.

To explain the nature of neutron-rich matter across a range of densities, as seen in the crust of neutron stars, an interdisciplinary approach is essential in order to integrate low-energy nuclear experiments and theory with knowledge from astrophysics, atomic physics, computational science, and electromagnetic and gravitational-wave astronomy. The nuclear input to this mix is essential. It includes studies of nuclear matter at both supranuclear and subnuclear densities by means of heavy-ion collision experiments, the analysis of high-frequency nuclear oscillations, and *ab-initio* approaches to the equation of state of nuclear matter.
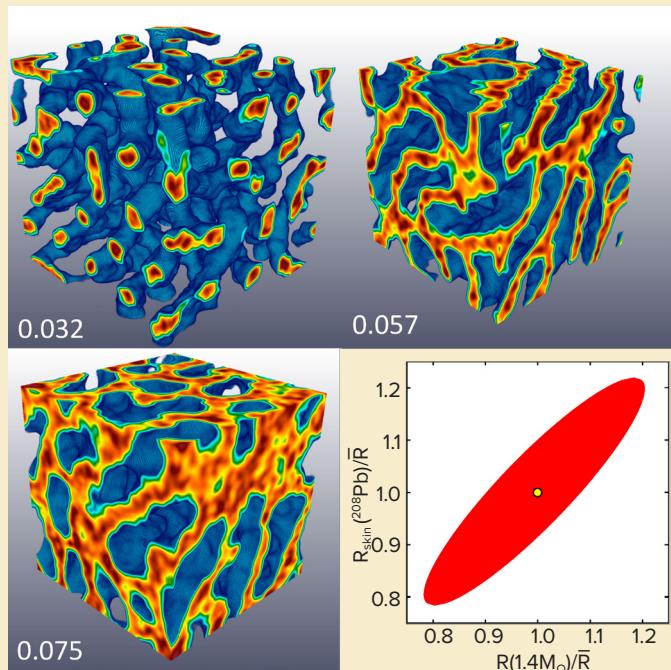
Sidebar 3.2: Neutron Stars, Nuclear Pasta, and Neutron-Rich Nuclei and Matter

Neutron stars are extraordinary nuclear laboratories. They are more massive than our sun but only measure about 20 km across. The tremendous gravitational forces squeeze matter in its core to supranuclear density (>7×10^{14} g/cm^3), exposing properties of the nuclear force not otherwise encountered. Remarkably, our very existence depends on these properties as the heaviest neutron-rich elements in the universe are likely synthesized in the vicinity of neutron stars during their birth in a supernova and during rare collisions with other neutron stars or black holes.

A neutron star is 18 orders of magnitude larger and 55 orders of magnitude more massive than a nucleus such as ^{208}Pb. Nevertheless, both the star and the nucleus have the same constituents, the same strong interactions, and the same relationship between pressure and density. As a result, a remarkable model correlation is observed between the calculated neutron radius of ^{208}Pb and the neutron star radius. This correlation is illustrated in the figure.

Because neutron stars are so compact, they heat, flare up, and cool rapidly, making them easy for astronomers to study. For example, the outer layers of neutron stars that intermittently accrete from a sunlike companion star are observed to cool over a few years' time. This rapid cooling suggests that these outer layers are good thermal conductors. At lower densities near the surface of the star, the outer region, known as crust, is made of conventional atomic nuclei. In the denser regions of the crust with densities near 10^{14} g/cm^3 (100 trillion times that of water), these nuclei start to touch. Here, strong nuclear attraction and electrostatic repulsion compete to rearrange nearly spherical nuclei into flat platelike (lasagna), rodlike (spaghetti), or more complex shapes, collectively referred to as the nuclear pasta. Theoretical simulations of nuclear pasta (see figure) have shed new light on the structure of matter in this regime, the extent of disorder that can be sustained, and the influence of superfluidity and collective motion on the matter's low temperature properties. These developments have far-reaching implications that extend beyond nuclear physics. By establishing connections between nuclei and neutron stars, advanced theory has shown in recent years that properties of neutron-rich nuclei and neutron-rich matter influence diverse observable phenomena such as supernova neutrinos, heavy-element nucleosynthesis, electromagnetic radiations from transient astronomical events, and the generation of gravitational waves.

Top and bottom left: Molecular dynamics simulations of nuclear pasta in a $(100\,fm)^3$ *cube containing 38,400 nucleons. The colors indicate the density of nuclear matter from blue (low) to brown (high). The neutron density (in* fm^{-3}*) is indicated. An average nuclear matter density is* $0.16 fm^{-3}$*. Bottom right: A model correlation between the neutron radius of* ^{208}Pb *and the radius of a 1.4 solar-mass neutron star.*

TESTS OF FUNDAMENTAL SYMMETRIES IN RARE ISOTOPES

By producing isotopes with enhanced sensitivity to fundamental symmetries, opportunities are provided for discovering physics beyond the Standard Model. The quest for new physics is discussed in Chapter 5; here, we highlight the role played by rare isotopes in extracting the relevant science.

Of thousands of different isotopes undergoing beta decay, a handful of rare isotopes with similar numbers of protons and neutrons are the best laboratory to study the universal strength of the weak force. An important advance came when the results of nuclear measurements of "superallowed" beta decays, evaluated with small theoretical corrections, showed that a key part of the weak force is the same within 1 part in 10 thousand for a sample of 14 different nuclear decays studied. Future measurements in heavier $N{\sim}Z$ nuclei below ^{100}Sn, where the theoretical corrections are largest, will be helpful in improving theory.

Heavy radioactive atoms hold promise in the search for an electric dipole moment, one of the crucial probes for physics beyond the Standard Model. This is expected to have a very weak signal, but an enhancement of order 100–1000 (or more) is possible in nuclei that have pearlike shapes, such as ^{225}Ra. One of the near term goals of the field is to identify the best candidates for enhancement and characterize their structure.

One of the hallmarks of the modern approach to nuclear theory is the consistent description of currents and forces, with two-body currents being akin to three-nucleon forces. Inclusion of two-body currents has explained the quenching of the axial coupling constant g_A, a long-standing problem. A crucial challenge for nuclear theory will be to deliver a precise and accurate estimation of the nuclear matrix element for neutrinoless double beta decay, which is crucial if the neutrino mass is to be extracted from a measured half-life. Current predictions carry an unacceptable uncertainty of 100% or more, but developments in computational many-body theory offer the prospect of significantly more accurate calculations of the matrix elements for complex nuclei.

THE PROSPECT

FRIB will provide access to unexplored regions of the nuclear chart, where new phenomena like large neutron skins and new collective modes will guide the development of a comprehensive picture of the atomic nucleus. With the neutron drip line within reach for nuclei as heavy as A=120, researchers will be able to study 80% of all isotopes predicted to exist for elements below uranium. From this vast pool, key isotopes can be chosen for targeted experiments aimed at enhancing or isolating the answer to specific physics challenges.

While FRIB is the top priority of the nuclear structure and reactions community, there are other capabilities needed to reach the scientific goals of the field. The community developed a coherent plan that pursues key scientific opportunities by leveraging existing and future facilities. The plan involves continuation of forefront research activities, development of needed theory, and initiation of a focused set of new equipment initiatives. The reacceleration of secondary beams is a key element of the FRIB complex, but it is also needed currently at the NSCL. This and other upgrades to the NSCL, ensuring effective operation of this facility, are essential to exploit the full discovery potential with radioactive beams, which include those available at present and in the FRIB era. The ATLAS stable beam facility has world-unique capabilities that will enable necessary precision studies near stability and at the limits of atomic number. The electron beam at JLab provides a unique capability for probing the short-range part of the nuclear force in nuclei. The university accelerator labs have a special role. They contribute cutting-edge science, focused research programs of longer duration, and critical developments of techniques and equipment, all combined with hands-on education. In addition to these facilities, the community has developed exciting ideas for new equipment key to the future research effort. Not all can be realized immediately, but a targeted suite to address the highest priority research programs is needed. Instruments such as GRETA, HRS, and SECAR (a recoil spectrometer for nuclear astrophysics research) will be essential to realize the scientific reach of FRIB.

A strong theory effort needs to go hand in hand with future experimental programs. The theory roadmap for this area involves the extension of *ab-initio* and configuration interaction approaches to medium-heavy nuclei, the quest for a universal interaction in nuclear density functional theory that will describe all nuclei up to the heaviest elements, and a comprehensive theory for nuclear reactions. FRIB will provide unprecedented access to key regions of the nuclear chart where the new measurements will challenge established concepts, highlight shortcomings, and, inevitably, guide the development of a new theoretical picture of atomic nuclei. The proposed FRIB Theory Alliance, a modest-scale national effort comprising a broad theory community, will, therefore, be important for the success of FRIB. Finally, to reach the scientific goals, high-performance computing, the third leg of this field, will be crucial.

What are practical and scientific uses of nuclei? Within the large territory of nuclei, with behaviors ranging from simple to complex, there are many intellectual connections and benefits to other fields of science. In addition to the discovery aspect, the basic research in this subfield often has direct bearing on many branches of science and societal relevance to national security, energy, medicine, and industry. These connections are discussed in detail in Chapter 9, Broader Impacts.

4. Nuclear Astrophysics

Nuclear astrophysics addresses the role of nuclear physics in our universe. It is a field at the interface of astrophysics and nuclear physics that is concerned with the impact of nuclear processes on the evolution of the universe, the development of structure, and the build-up of the chemical elements that are the building blocks of life. It is a broad discipline that can identify new observational signatures probing our universe. It studies the constituents, including dark matter and baryonic matter, and elusive particles such as weakly interacting massive particles (WIMPs) and neutrinos. Nuclear astrophysics can identify the conditions at the very core of stars and provide a record of the violent history of the universe.

Large supercomputers facilitate the development of new generations of complex tools and models for interpreting the multiple nuclear processes that drive the evolutionary progress from the early seconds of the Big Bang to the first and many generations of subsequent quiescent and explosive stellar events that led to the formation of the elements on our earth.

Nuclear astrophysics stands on the forefront of scientific developments. New initiatives include the development of experimental tools that open new vistas into the nuclear processes that take place at extremely low energies during the long evolutionary phases of stars and in explosive events, from novae to supernovae and from X-ray bursts to superbursts.

Nuclear physics plays a unique role in astrophysics. A few of the major achievements and accomplishments of the field over the last decade include the following:

- Big Bang nucleosynthesis and simple neutrino physics made the determination of the baryon content in our universe possible on the basis of observational data and cosmic microwave background anisotropy measurements.

- The observation of early stars and their distinctively different abundance patterns from today's stars provide us with important clues on the origin of the elements.

- The observation of the unique r-process patterns in very metal-poor, old stars defines a unique site; the two possible candidates are core-collapse supernovae and merging neutron stars.

- Solving the solar neutrino problem established that neutrino flavor physics is fundamental in astrophysics. This understanding verified that neutrinos are important tools for probing the interior of our sun and that they will provide new opportunities for probing other stellar events.

- A number of successful low-energy reaction experiments were completed using university accelerators and deep underground accelerators for shielding the cosmic-ray background. The results often showed startling differences between predicted and observed results.

- A deeper understanding of the physics of neutron stars was achieved through the observation and interpretation of X-ray bursts and the experimental study of high-density nuclear physics conditions using radioactive beams.

- New experimental tools and methods were developed for the measurement of nuclear masses, decay processes, and reactions far off stability, all with unprecedented accuracy.

- The use of high-performance supercomputers has revolutionized the modeling of stellar evolution, core collapse supernovae, compact object physics, neutrino astrophysics, and the emergence of structure in the universe.

The symbiotic relationship between nuclear physics and astrophysics continues to pose new questions, providing new scientific opportunities for the next decade:

- Where do the chemical elements come from, and how did they evolve?

- How does structure (e.g., stars, galaxies, galaxy clusters, and supermassive black holes) arise in the universe, and how is this related to the emergence of the elements in stars and explosive processes?

- What is the nature of matter at extreme temperatures and densities? How do neutrinos and neutrino masses affect element synthesis and structure creation in the history of the universe?

- What is dark matter, and how does it influence or is it influenced by nuclear burning and explosive stellar phenomena?

All of these questions are interrelated, sometimes tightly coupled, and nuclear physicists are making unique contributions in answering them.

THE ORIGIN OF THE ELEMENTS

The origin of the elements is one of the fundamental questions in science. The solar abundance distribution of the elements is a product of multiple nucleosynthesis events over the history of the universe. The identification of these processes and their astrophysical sites has been one of the main goals of the field (Figure 4.1).

Within the first few minutes of the Big Bang, in a rapidly expanding early universe, the primordial abundance distribution emerged, consisting of hydrogen, helium, and traces of lithium. These abundances provide a key signature for our understanding and interpretation of the early universe.

How did the universe evolve from an environment of only three elements to a world with the incredible chemical diversity of 84 elements that are the building blocks of planets and life? These elements were formed at the high density and high temperature conditions in the interior of stars. The first stars emerged a few hundred million years after the Big Bang. A lack of nuclear fuel caused their fast collapse, forming the first generations of supernovae. Recent observations detected the dust of one of the very early supernova explosions in our galaxy; a spectroscopic analysis of trace elements shows that carbon and oxygen, the elements that provide the basis for biological life many billions of years later on our earth, had been formed. Many star generations followed; as observations show, with each generation the abundance of heavy elements increases. This synthesis of the elements in the interior of stars follows a nuclear fuel cycle that is dictated by the fuel available and by the balance between the gravitational forces of the star and the interior pressure generated by the nuclear energy released. These conditions are reflected in the different burning phases that characterize the evolution of each star during the course of its life.
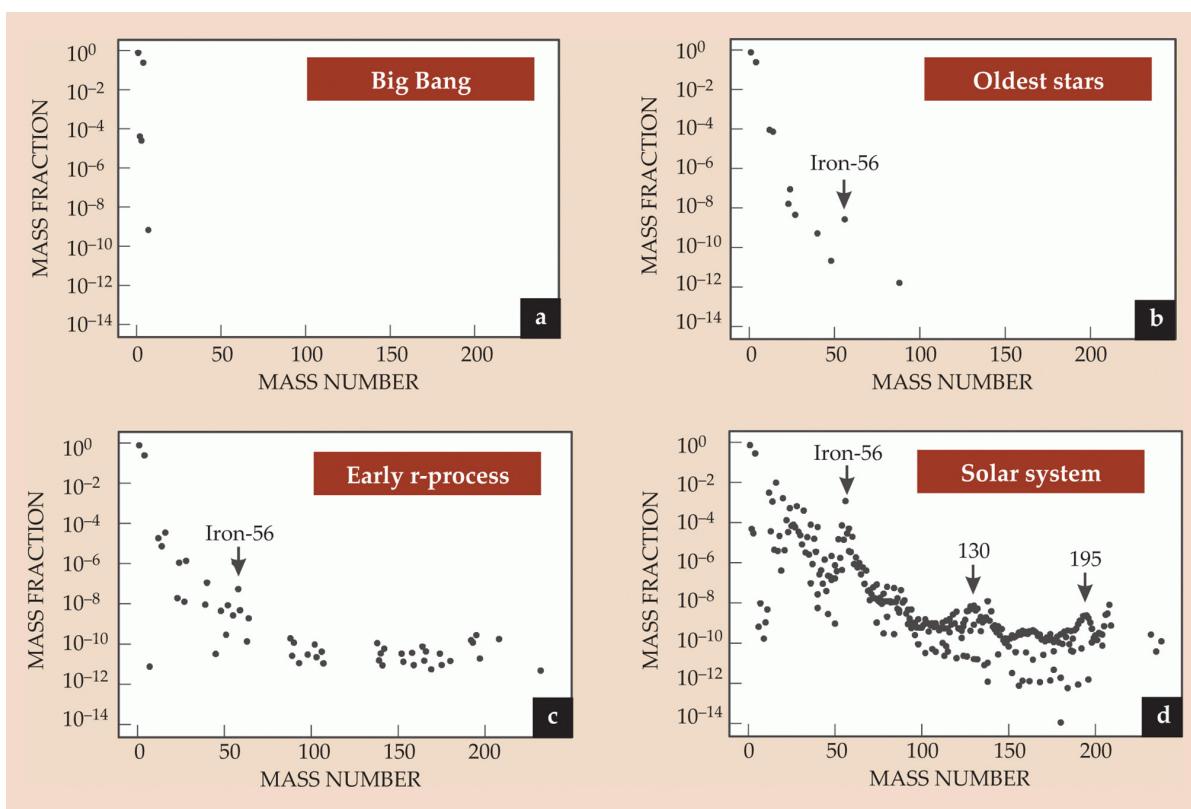
Figure 4.1: *Development of the elemental abundances from the primordial abundances of the Big Bang, the abundances observed for the earliest star generations, the appearance of r-process abundance patterns in very old stars, to the solar abundances observed today. Image credit: H. Schatz, Physics Today.*

THE LIFE OF STARS

The first phase of hydrogen burning characterizes the so-called main sequence stars. Low mass main sequence stars generate energy through the pp-chains, direct fusion reactions between hydrogen isotopes forming helium. Weak interaction processes in the reaction sequence produce neutrinos that have been observed with neutrino detectors such as Sudbury Neutrino Observatory (SNO), SuperKamiokande, and Borexino. These measurements provide a unique view into the interior of stars. For more massive stars the pp-chains are not sufficient in providing the energy necessary for stabilizing the star against collapse. In these cases, a second catalytic reaction sequence—the CNO cycles—dominates the conversion of hydrogen into helium. The CNO cycle stabilizes stars more massive than our sun, such as Sirius, Vega, and Spica to name just a few visible in the Northern Hemisphere. The reaction rates defining the CNO cycle are highly uncertain and require experimental confirmation.

When a star's hydrogen fuel diminishes, the core contracts, and the nuclear burning zone extends outwards. The star evolves into a red giant. The increase in the temperature and density of the stellar core sets the stage for the next burning cycle. Helium is the ash of hydrogen burning; it will undergo fusion to carbon through the triple-alpha-process and to oxygen through a subsequent alpha capture (Sidebar 4.1). The best known example of a red giant star is Betelgeuse in the Orion constellation. When all the helium in the core is converted to carbon and oxygen, further energy production has to come from the fusion reactions involving these heavier nuclear species. These reactions can occur only in massive stars as shown in Figure 4.2. In low mass stars the nuclear burning stops, and they contract under their own gravity into white dwarfs that are stabilized by their internal electron capture. In more massive stars, temperature and density conditions can be reached where nuclear burning of carbon, oxygen, and even heavier species can proceed. This phase is followed by neon burning, oxygen burning, and silicon burning, all proceeding toward nuclei in the iron peak (i.e., species at the peak of nuclear binding energy).

The rates of nuclear reactions that dictate the fuel consumption, and, therefore, determine the energy production and lifetime of the various stellar evolutions phases as well as those that determine the change in chemical composition, still carry large uncertainties. These reactions have extremely low cross sections. Their measurement can only be pursued in deep underground laboratories that provide shielding from cosmic radiation background. Enormous progress has been made over the last decade in developing new techniques for these studies, but many critical questions remain unanswered. **A high-intensity underground accelerator would be essential for addressing the broad range of experimental questions associated with the nucleosynthesis in stars.**
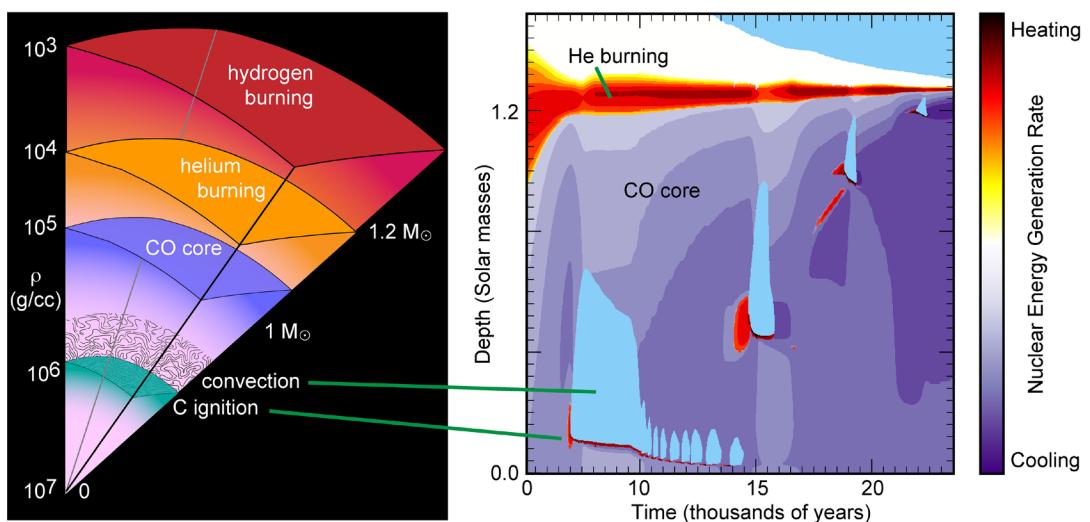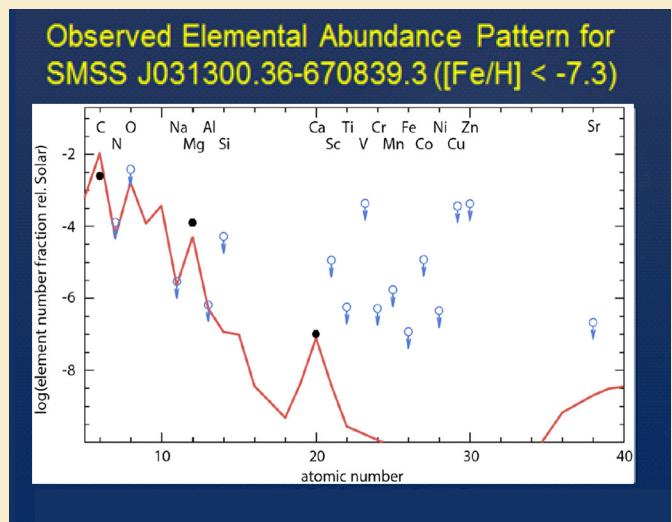
Figure 4.2: *Super asymptotic giant branch stars form the boundary between stars whose final fate is a white dwarf and stars whose final fate is a massive star supernova explosion. Left: Structure of a super asymptotic giant branch star with a carbon/oxygen burning core, surrounded by a layer of helium, which is then surrounded by a hydrogen envelope. The right-hand figure demonstrates the time evolution of several episodes of carbon burning flashes travelling towards the core at that stage. Regions in red are undergoing vigorous burning, purple are regions which are cooling, and light blue are regions of convection. Image credit: Rob Farmer, Carl Fields, Frank Timmes.*

Sidebar 4.1: The Carbon-to-Oxygen Ratio in Our Universe

A fundamental question for nuclear astrophysics is the ratio of ^{12}C to ^{16}O that emerges in the very first generations of stars. This ratio is not only important for the development of the chemical building blocks of life but also for the entire scheme and sequence of nucleosynthesis events as we imagine them now. The carbon-to-oxygen ratio determines the sequence of late stellar evolution phases for the massive stars that give rise to core collapse supernovae. It determines the ignition and burning conditions in Type Ia (thermonuclear) supernovae, and it dictates conditions for the ignition of so-called superbursts observed in accreting neutron stars. Carbon induced reactions are, therefore, of extreme importance for our entire understanding or interpretation of nucleosynthesis patterns and the identification of nucleosynthesis sites.

Present extrapolation of the reaction rates associated with the $^{12}C/^{16}O$ ratio from the presently existing data depends very much on the reliability of nuclear structure and reaction models, which introduce orders of magnitude uncertainty into the predictions. This problem has been well known for decades, and its solution requires new experimental efforts in a cosmic-ray-background-free (deep underground) environment to provide the necessary experimental conditions for putting to rest the question associated with low-energy carbon capture and fusion reactions.

The oldest known star (arrow in left picture), with an age of about 13.6 billion years, is located in our Milky Way at a distance of 6000 light years from the sun. Its abundance pattern (right picture) proves early stellar nucleosynthesis of light elements like carbon and oxygen. Image credit: Timothy Beers.

THE DEATH OF STARS

Another frontier in nuclear astrophysics is the study of nuclear processes that drive stellar explosions. There are two kinds of explosions, the core collapse of massive stars at the end of their lives and thermonuclear explosions as a consequence of stellar accretion. The core collapse of a massive star is caused by neutrino energy losses exceeding the energy generation rate from nuclear burning. The cores of these stars are refrigerated, their entropy is lowered, and the internal pressure support is entirely defined by relativistically degenerate electrons. According to W. A. Fowler and F. Hoyle, the cores of these stars are "trembling on the verge of instability." The core will collapse, either through that instability or by destabilization through electron capture on heavy nuclei.

The core density will reach nuclear densities in about one second, producing a hot proto-neutron star generating a high flux of neutrinos. While the core remains as a neutron star, the neutrino flux, in total comprising about 10^{58} neutrinos, drives energy deposition in the surrounding material and produces a supernova explosion. Detection with the large detectors of today and the future of such a neutrino burst from a nearby supernova could provide critical insights into the explosion mechanism and valuable information about the properties of neutrinos. The core bounce conditions

for the in-falling material in this collapse scenario depend on the equation of state, particularly on the incompressibility of neutron star matter. The bounce-initiated and neutrino-revived shockwave traverses the outer layers of the star, generating conditions that lead to multiple nucleosynthetic pathways behind the shock (see Sidebar 4.2).

Thermonuclear explosions are driven by accretion of light element fuel in binary star systems onto a compact star, either a white dwarf or neutron star whose abundance pattern is defined by its nucleosynthesis history. Such events are observed as novae and X-ray bursts, respectively. Within a few seconds the light fuel material ignites and is converted by rapid alpha and proton capture reactions to a heavy element isotope distribution. The timescale of the burst, the endpoint, and the final abundance distribution depend upon the nuclear reaction and decay rates along the reaction path. Measurements of the key reaction cross sections are crucial for interpreting the burst characteristics, but successful measurements require the high beam intensities anticipated for FRIB.

The Type Ia supernova is interpreted as a thermonuclear-energy-driven explosion. In this case, carbon/oxygen burning ignition takes place near the center of a white dwarf star. Ignition and propagation of the burning front in this explosion depend on the abundance composition of post-helium burning stars. The rates for the fusion reactions between carbon and oxygen nuclei that are important for igniting and driving the burning front are uncertain for the temperature range anticipated for such an event. The flame front propagation speed depends on additional reactions, namely alpha capture reactions that require further experimental studies.

Merging neutron stars can be considered an extreme case of accretion. Two neutron stars in a double star system spiral into each other under the influence of their gravitational potential. The merging of the two stars generates extreme density conditions, prodigious neutrino emission as in core collapse supernovae, and, likely, very high neutron flux conditions suitable for a rapid neutron capture process, or r-process, with the reaction products being dynamically ejected by tidal and pressure forces during the merger. Detecting these events and the event rate with new instruments such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) will provide us with important

information on the possibility of identifying these events as r-process sites (see Sidebar 4.3).

All these explosive events occur rapidly on a timescale of a few seconds. This prevents radioactive nuclei formed in the explosion from decaying within this short period. They become part of the sequence of nuclear reactions that develop far beyond the limits of nuclear stability. A study of these reactions, and of the decay and structure characteristics of the nuclei along the reaction path, provides fundamental insight into the nature of these processes, the rapid timescale of the explosion, the associated energy release, and, of course, nucleosynthesis. **FRIB will provide the beam intensities for a direct study of key reactions and key nuclei necessary for understanding the specific nature of the nuclear pathway during an explosive event and, through comparison with the emerging abundance distribution, the nature of the astronomical site and the conditions during the explosion.**

THE MATTER OF NEUTRON STARS

The physics of neutron stars is of particular interest to the nuclear physics community. Indeed, the structure and composition of neutron stars in hydrostatic equilibrium are uniquely determined by the equation of state (EOS) of neutron-rich matter, namely, the relation between the pressure and energy density. Measurements of neutron-star masses and radii place significant constraints on the EOS (Figure 4.3). Conversely, future measurement of both masses and the neutron-rich skin of exotic nuclei at FRIB will provide critical insights into the composition of the neutron star crust.
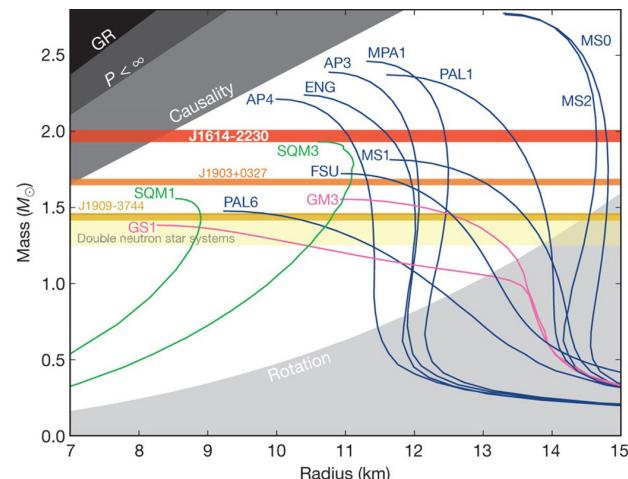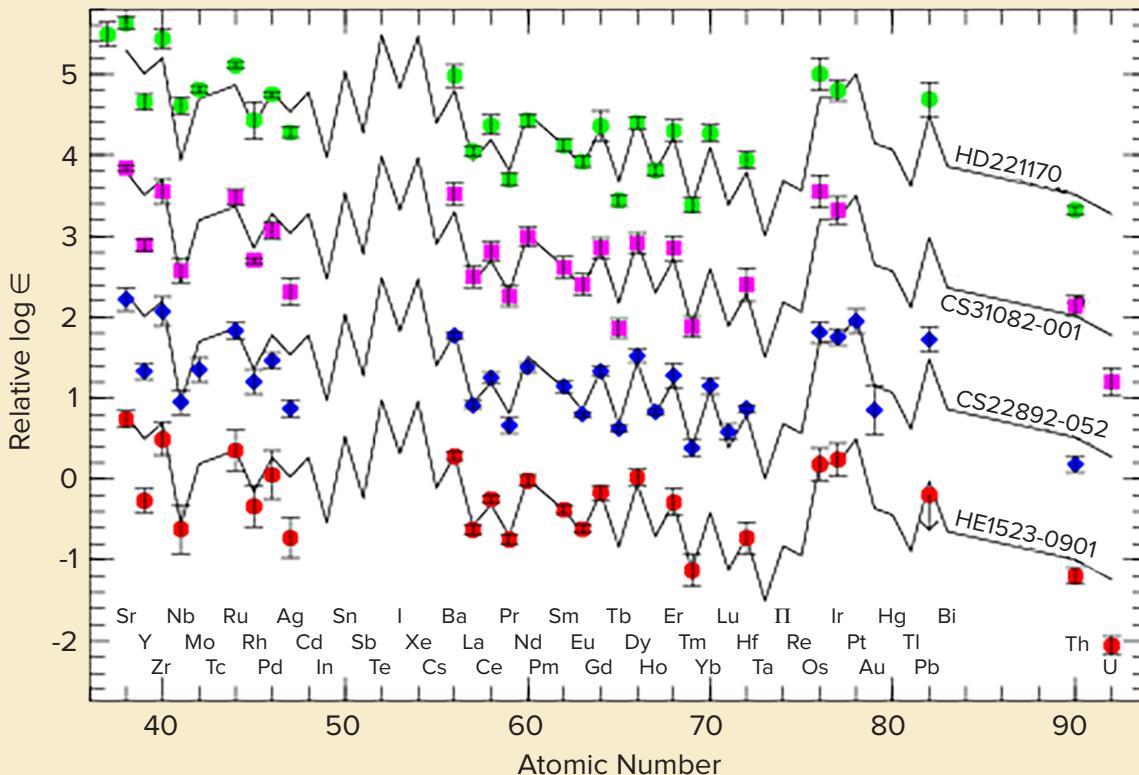
Figure 4.3: *Astrophysical measurements of masses and radii of neutron stars can provide key insights into the equation of ultra-dense neutron star matter. Image credit: P.B. Demorest et al. Nature 467, 1081 (2010).*

Sidebar 4.2: The Origin of Heavy Elements

A fundamental question for nuclear astrophysics is the origin of the neutron-rich elements heavier than iron. These heavy elements are mostly produced either by a slow neutron capture process (the s-process) that takes place during helium and carbon burning phases of stellar evolution or by a rapid neutron capture process (the r-process) that requires a much higher temperature and density environment. The latter can only be associated with violent events generating high neutron excess. The masses (binding energies) and the lifetimes of nuclei along the r-process path are the most important microscopic parameters for theoretical simulations. These inputs are currently taken from extrapolations based on theoretical models. Experiments at existing facilities on isotopes near the r-process path show us that these extrapolations are highly uncertain and may lead to faulty conclusions about the r-process conditions.

New constraints are coming from large aperture observatories such as the Hubble Telescope, the Very Large Telescope, Keck, Subaru, and Magellan observatories. Observations of early-generation stars

(see figure) indicate a heavy-element abundance distribution that matches the patterns in the higher mass range, albeit not the absolute abundances of the r-process element abundance distribution in our sun. This suggests that there may be a unique site for the r-process. The nature of the actual astrophysical site of the r-process has been a matter of fierce scientific debate for many decades. Both the neutrino wind driven ejecta from a core collapse supernova and the violent collision of merging neutron stars could conceivably provide conditions for an r-process to occur—depending on many uncertain issues in nuclear and neutrino physics. Improved nuclear physics data from FRIB are crucial to make detailed predictions and to determine potential features for identifying the actual site. The r-process site is a critical issue in which observational, modeling, and experimental data are essential to reach a solution to an important and long-standing astronomical problem. The nuclear physics studies, in combination with signals from Advanced LIGO, will determine whether neutron star mergers can be a significant source of r-process elements.

Abundance pattern of heavy elements in old, metal-poor stars compared to the relative solar r-process distribution (solid lines). The absolute scales have been chosen arbitrarily for better presentation. Image credit: Anna Frebel.

The cooling behavior of neutron star transients from X-ray bursts are determined by the energy budget of the nuclear processes in the neutron star crust. Electron capture reactions, driven by the ever-increasing density conditions, drive the abundance distribution to the neutron-rich side. Such electron-capture reactions change the internal energy budget and affect the cooling behavior of matter in the neutron star crust. These electron-capture processes can be studied by means of charge-exchange reactions on neutron-rich isotopes. At extreme densities, density-driven or pycno-nuclear fusion between very neutron-rich nuclei from carbon to magnesium can occur in the deeper layers of the neutron star crust. This should be associated with another release of energy that should be reflected in the thermal, neutrino, or gravitational-wave-related energy release in the neutron star transient.

For the foreseeable future, neutron star crust models will have to rely on a combination of experimental and theoretical data, especially modifications to masses and effects such as superfluidity, pasta phases, and neutrino emissivity that will have to be calculated using nuclear theory. Important developments are mass and drip line predictions by modern Density Functional Theory, which can provide estimates for theoretical uncertainties that can be taken into account in astrophysical models. Shell model calculations can provide relatively reliable electron capture and beta decay strength, but the effective interactions used need to be tested with data on neutron-rich nuclei, especially in the electron capture direction.

The nuclear matter EOS is a fundamental aspect of matter but is not well known. Neutron star properties depend sensitively on the EOS of cold nuclear matter in a density range of the nuclear saturation density. Particularly uncertain is the density dependence of the symmetry energy—the energy difference between nuclear matter with protons and neutrons and pure neutron matter. The symmetry energy determines a range of neutron star properties such as cooling rates, the thickness of the crust, the mass-radius relationship, and the moment of inertia. The characterization of symmetry energy through experiment is, therefore, a crucial step towards our capability of interpreting neutron star matter and its characteristics.

Laboratory measurements are necessary to constrain nuclear matter compressibility and the symmetry energy.

Likewise, studies of masses, giant resonances, dipole polarizabilities, and neutron skin thicknesses of neutron-rich nuclei will provide key insights for astrophysics. **Extending such measurements to more neutron-rich nuclei and increasing the precision, especially of neutron skin thickness measurements, will be an important component of FRIB studies.**

CONNECTIONS: DARK MATTER, QCD PHASE DIAGRAM, WEAK INTERACTIONS, AND NEUTRINOS

Nuclear structure and nuclear response issues can be important in efforts aimed at direct and indirect detection of dark matter. Laboratory direct detection schemes rely on detecting the energy deposition caused by dark matter WIMPs scattering via the neutral current weak interaction on silicon or germanium atoms or on argon or xenon atoms in liquid noble gas experiments as summarized in Chapter 5, Fundamental Symmetries and Neutrinos. Nuclear response calculations indicate that there may be significant differences in expected scattering cross sections and interaction rates, depending on the target nuclei involved, especially in the spin-dependent channels. This effort is being complemented by low-energy studies at nuclear accelerator facilities using neutron beams or other probes to test the predicted detector responses and achieve a better sensitivity for the signal analysis. These nuclear physics aspects will need to be addressed before any signals from the direct detection experiments can be reconciled with astrophysical models for the local dark matter composition and distribution.

Likewise, indirect detection of WIMP annihilation from gamma-ray fluxes in the galactic center and in the galaxy's bulge and dark matter halo is complicated by cosmic-ray-generated background. Gamma-ray emission from millisecond pulsars (neutron stars) matches closely the spectrum expected from WIMP annihilation. Millisecond pulsars are old as they are the endpoints of the evolution of neutron stars. Understanding this source of background for indirect detection of dark matter, therefore, couples into many of the issues of neutron star production, space motion, and associated galactic chemical evolution described above.
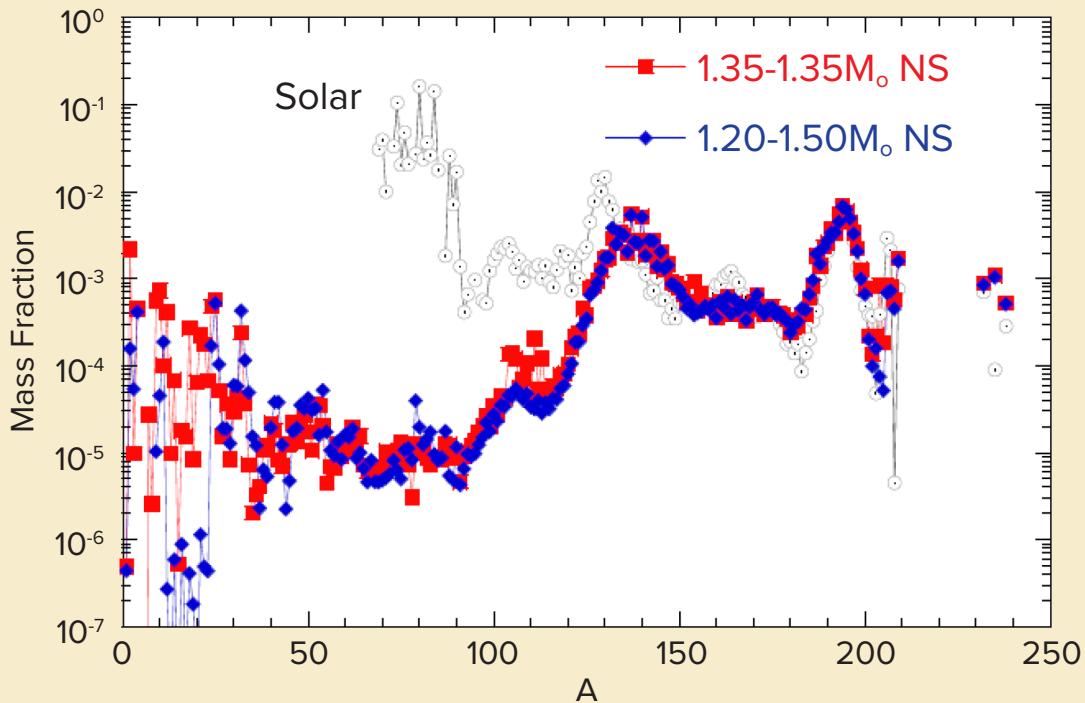
Astrophysical observations can probe environments with extreme conditions of temperature and density. These conditions are sometimes difficult or even impossible

Sidebar 4.3: Advanced LIGO and Nuclear Physics

The detection of gravitational radiation from the violent merging of neutron stars in binary systems could have profound implications for nuclear astrophysics. We expect such mergers to be rare events in a galaxy like ours, perhaps happening once per 10 thousand to 1 million years. Fortuitously, the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) will very soon be able to detect gravitational waves from these events out to a distance of 200 megaparsecs, a volume encompassing some millions of galaxies. In fact, the first observable from this observatory will be the *rate* of neutron star mergers, a key parameter in differentiating between sites proposed for the origin of the heaviest nuclei, like uranium. We have known for more than 50 years that roughly half the nuclei with mass numbers greater than 100 originate in the r-process. It is a vexing problem that we know the r-process happens, but we do not know *where* it happens. Proposed production sites have centered on astrophysical environments either having abundant free neutrons or where neutrino or nuclear reactions can *mine* neutrons from lighter nuclei. Core collapse supernovae, which happen about once per century in

our galaxy, and the much less frequent neutron star mergers are the leading candidate sites. Whatever site or sites contribute, 10 thousand solar masses of r-process nuclei must be synthesized in our galaxy in 10 billion years. That datum, combined with an Advanced LIGO-inferred observed merger rate, could tell us whether mergers are a significant r-process source. If the r-process nuclei originate in neutron star mergers, the observed local rate of these events, combined with abundance observations at high redshift from the next generation of ground-based telescopes, may suggest a higher rate of compact object mergers in the past.

The gravitational waves that Advanced LIGO will observe come from violent motions of matter at nuclear density. As a result, the details of the observed neutron star in-spiral gravitational-wave signal may provide insights into the nature and behavior of ultradense neutron matter and the general conditions in the merger environment. In both mergers and core collapse supernovae, weak interactions, neutrino flavor physics, and neutrino-nucleus processes are key ingredients in understanding r-process nucleosynthesis. Knowing more about the merger environment can help guide this research.

Nuclear abundance distributions as a function of atomic mass of the ejecta for two different combinations of neutron star mergers. The distributions are normalized to the solar r-process abundance distribution. Image credit: Stephane Goriely.

to reproduce in a terrestrial laboratory. Therefore, astrophysical studies of the properties of nuclear matter may be uniquely complementary to laboratory probes at JLab, RHIC, and FRIB. On the other hand, for example, our understanding of the early quark-gluon phase of the universe and in the core of neutron stars may profit substantially from relativistic heavy-ion experiments at RHIC, probing the phase diagram for strongly interacting matter.

The QCD transition in the early universe, where chiral symmetry is broken and quarks and gluons are annihilated/incorporated into color singlets, is predicted by LQCD calculations to be a crossover transition and to occur when the universe is tenths of microseconds old. At this point, the causal horizon scale (sometimes referred to as the "size of the universe") is about 20 km and contains a total mass-energy of ~1 solar mass, all made up of relativistic particles, mesons, and nucleon-antinucleon pairs which are all touching and overlapping. A causal horizon volume at this epoch is in essence an ultra-high entropy neutron star.

The significant change in the numbers of relativistic degrees of freedom at this epoch (roughly a factor of three) has important implications for the histories of fluctuations and potential beyond-Standard-Model particle relic densities.

As described above, weak interaction processes involving nuclei are at the heart of core collapse supernova and neutron star merger physics. Neutrinos produced in these environments more than make up for the *weakness* of the weak interaction with their huge numbers. In fact, neutrinos can carry and transport the bulk of the energy and entropy (disorder) in these environments. In turn, this makes unknown weak interaction physics in the nuclear physics realm and in the neutrino sector potentially important players. For example, collective neutrino flavor oscillations may take place in these environments, and this phenomenon is sensitive to the neutrino mass hierarchy.

There are aspects of nuclear structure physics at extreme temperatures and densities that impact the role of weak interactions in astrophysical environments. For example, the heavy, neutron-rich nuclei, which are the principal targets for electron capture in the pre-collapse and collapsing core of a supernova, reside in very highly excited states. Weak interaction strength functions in

these exotic nuclear species and the associated high temperature nuclear partition functions remain key unknowns in our models for core collapse supernova explosions and associated nucleosynthesis. **Charge exchange reactions performed at FRIB can be an important guide to theorists tackling these issues.**

5. Fundamental Symmetries and Neutrinos

Discovering and characterizing the basic forces of nature have been at the forefront of physics research for centuries. From the apple falling in Lincolnshire, England, to the appearance of the Higgs boson at CERN, these endeavors continue to the present day. Nuclear scientists have played a major role in this effort, from characterizing the necessary ingredients and the properties of the nuclear force to discovering the violation of parity symmetry in nuclear decay. More recently, they have focused on trying to understand the unusual properties of neutrinos, searching for new violations of basic symmetries in subatomic forces and performing precision tests of the present Standard Model of the strong, weak, and electromagnetic forces, especially in nuclear systems.

The Standard Model has been extraordinarily successful in accounting for a wide range of phenomena, and most of its parameters have been precisely pinned down in recent years. Data at the Large Hadron Collider have provided direct evidence that the Higgs boson provides mass to elementary particles, even though that accounts for very little of the masses of protons and neutrons and also may not account for the very tiny neutrino masses. The mass differences between neutrino species and the extent of mixing among them have been accurately measured in experiments, some of the most critical led by nuclear scientists. Nevertheless, important issues remain unresolved, such as the particle-antiparticle nature of the neutrino, the origin of the cosmic matter-antimatter asymmetry, and the composition and interactions of dark matter. Among these issues, nuclear physicists have focused on four key questions, for which nuclear science brings a unique arsenal of experimental and theoretical expertise and tools:

- **What are the absolute masses of neutrinos, and how have they shaped the evolution of the universe?**

- **Are neutrinos their own antiparticles?**

- **Why is there more matter than antimatter in the present universe?**

- **What are the unseen forces that disappeared from view as the universe expanded and cooled?**

The 2007 Long Range Plan described the new Standard Model initiative as a means to begin addressing these questions. This initiative included a "targeted program of experiments" which has begun. Often these experiments are very challenging as they push their sensitivities to new extremes. They frequently require development of new technologies in order to achieve their goals and typically require innovative R&D programs.

Developing the new Standard Model that resolves some of the puzzles is, of course, a task that reaches across the lines of various subfields of physics. While the discovery of the Higgs boson at the LHC was a triumphant validation of a key prediction of the Standard Model, the nonobservation of any other new particles at the LHC leaves important unanswered questions, such as those discussed above. Against this backdrop, the low-energy, high-sensitivity fundamental symmetry and neutrino studies performed by nuclear scientists take on added significance. Studies in nuclei provide important, unique opportunities to discover symmetry violations. For example, the nuclear pairing force that provides added stability to nuclei with even numbers of neutrons and protons opens the possibility to observe very rare double beta decay processes. Observation of such a decay without the accompanying emission of neutrinos (so-called neutrinoless double beta decay) would unambiguously answer one of the questions above, signaling that neutrinos are their own antiparticles. Nuclear techniques, perfected through decades of searches for a tiny separation of positive and negative charges (i.e., an electric dipole moment) within the neutron, will dramatically advance our probes of another of the questions, concerning the origin of the cosmic matter-antimatter asymmetry.

In what follows, we first highlight recent accomplish-ments and progress in advancing this science. We then lay out an exciting future program for which there is a clear need to increase support for both experimental and theoretical effort within this subfield. We show how nuclear physics studies of neutrinos and tests of fundamental symmetries provide a unique opportunity for addressing the questions outlined above. The proposed research is described in three broad areas: neutrino studies, electric dipole moment searches, and precision measurements. These varied thrusts

along with nuclear theory complement each other to comprehensively address the key questions.

HIGHLIGHTS AND RECENT ACCOMPLISHMENTS

Over the past decade, nuclear scientists working in this subfield have overseen a remarkable period of progress and discovery. We highlight this progress in the following; its significance and implications will become apparent in subsequent sections.

Neutrinos and Their Properties

Half-life sensitivity in excess of 10^{25} years has been achieved in searches for a very rare type of nuclear decay: neutrinoless double beta decay. A nonzero signal would be an explicit violation of lepton number conservation and imply that neutrinos are their own antiparticles (Majorana particles). A longstanding claim for observation of neutrinoless double beta decay in ^{76}Ge has been essentially ruled out by new results from EXO-200 in the U.S., KamLAND-Zen in Japan, and GERDA in Europe. EXO-200 also made the first observation of ^{136}Xe two neutrino double beta decay. Major technical milestones towards the feasibility of a ton-scale next-generation experiment were achieved by CUORE, EXO, Majorana Demonstrator (MJD), and SNO+. KATRIN, the most sensitive apparatus yet conceived to measure the absolute scale of neutrino mass via tritium beta decay, has successfully passed commissioning phases. A new cyclotron radiation emission spectroscopy technique to measure the neutrino mass was demonstrated. Neutrinos from the primary proton-proton fusion process in the sun were directly observed for the first time by Borexino. The previously unknown neutrino mixing angle (θ_{13}) was determined using reactor neutrinos at Chooz in France, Daya Bay in China, and Hanbit (RENO collaboration) in South Korea.

Electric Dipole Moments

A new U.S. limit on the permanent electric dipole moment (EDM) of ^{199}Hg approaching 10^{-29} e-cm has been set. A nonzero signal would be a violation of time reversal symmetry, whereby the microscopic laws of physics cannot distinguish whether the arrow of time is moving forwards or backwards. Critical technical milestones have also been achieved in the search for the neutron's EDM at the Spallation Neutron Source at ORNL. New laser trapping techniques for the search of the ^{225}Ra EDM have been demonstrated with a first measurement.

Further Probes of the New Standard Model

MuLan made the world's most precise muon lifetime measurement and determined the weak interaction strength—the Fermi constant—to 0.5 parts per million, while MuCap confirmed the low-energy QCD-based theoretical prediction for muon capture on protons for the first time. The Qweak experiment at Jefferson Laboratory made the first direct measurement of the strength of the electron-proton weak force (a prediction of the Standard Model which had not directly been tested previously). A similar measurement that directly measured electrons scattering off individual quarks showed for the first time that the poorly known quark spin-dependent component of the electron-quark weak force is nonzero. Measurements of nuclear beta decays with particularly clean theoretical underpinnings resulted in new limits on the existence of spin-independent lepton-quark weak forces. Precision measurements of half-lives and major technical progress in atom and ion trapping techniques have been achieved for ^{6}He, ^{8}Li, and ^{37}K nuclei. Advances in the techniques to measure the free neutron lifetime with beams (resulting in an improved measurement) as well as with neutron traps coupled with the LANL development of an improved ultracold neutron source have set the stage for new measurements. A precision measurement of the neutron's weak force strength was made by UCNA at LANL, while emiT at NIST set the world's best limit on possible manifestations of non-Standard Model time-reversal-violating forces in neutron beta decay.

Theory

Progress in theory has been equally important. New tools for computing the cosmic matter-antimatter asymmetry have enabled constraints on supersymmetric models from EDM searches. The development and application of effective field theories to describe beyond Standard Model contributions to beta decay observables have enabled direct comparisons of low-energy and high-energy observables' sensitivities. The nonlinear collective mutual interactions of neutrinos in exploding stars were analyzed for the first time. A new framework was developed, based on effective interactions that respect the symmetries of QCD, to study the time-reversal and parity-violating interactions of nucleons and pions, with implications for the EDMs of neutrons, protons, and nuclei.

OPPORTUNITIES

The "targeted program of experiments" described in the 2007 Plan has blossomed, leading to important scientific results and paving the way for profound discoveries and key insights during the next decade. In particular, results from the current generation of neutrinoless double beta decay searches, in which U.S. nuclear physicists play major roles, along with technical progress, have set the stage for U.S. leadership of next-generation ton-scale experiments. The U.S.-led search for a permanent EDM of the neutron at the SNS has passed the essential technical milestones that put it on the path to a hundredfold improvement in sensitivity. Ultraprecise measurements of the muon's magnetism along with parity-violating asymmetries in neutron decay and polarized electron scattering have provided new tests of possible scenarios for the new Standard Model and opened the door to even more sensitive precision tests in the future.

The opportunities made available by this progress take on added significance in light of results from experiments at the high-energy and cosmic frontiers. The observation of the Higgs boson fills in the remaining missing piece of the Standard Model, but with the nonobservation of any of the other new particles that were predicted to exist in many proposed extensions, the question of how to advance beyond it remains open. It is possible that the new interactions involve relatively light degrees of freedom whose effects would first appear in high-sensitivity fundamental symmetry tests and neutrino property studies. Alternatively, the new physics could exist at a mass scale above that accessible at the LHC but still be discoverable in such studies. In addition, the prospect that cosmology becomes sensitive to the sum of masses of the neutrinos further underscores the importance of terrestrial measurements of neutrino masses and studies of their interactions. If a mismatch between results among these "frontiers" were observed, it could yield important insights about the role played by neutrinos in the early universe.

The prospects for fundamental discoveries and deep insights into the laws of nature through fundamental symmetry tests and neutrino studies have generated a growing level of excitement since the 2007 Long Range Plan. Realizing the opportunities for the next decade will require increased investments in both experimental and theoretical initiatives, including a

major investment in a next-generation neutrinoless double beta decay search. This latter project would provide the opportunity for a major discovery—lepton-number violation—at a sensitivity level consistent with the neutrino mass inverted hierarchy. Such a discovery would have profound ramifications for our understanding of the origin of the cosmic matter-antimatter asymmetry, the way in which neutrinos acquire mass, and the role of neutrinos in the early universe. An active worldwide effort, with significant U.S. involvement, is underway to determine the best technologies (in terms of sensitivity and background rejection) for a ton-scale experiment. It is anticipated that these developments will converge within the next 2–3 years, thus identifying the appropriate technologies for an optimized search. If the U.S. is to play a leadership role in this major discovery opportunity, a significant commitment will be required to begin construction of an experiment.

With this enhanced program of experiments and theory in fundamental symmetries and neutrinos, nuclear scientists could make major discoveries as well as sharply constrain the new Standard Model. This program would focus on determining the masses and other properties of neutrinos, searching for yet unseen violation of time-reversal invariance and lepton-number conservation, and revealing new types of interactions beyond the Standard Model.

Advancing this exciting portfolio of experimental and theoretical investigations will require increased and sustained support for research, including Major Items of Equipment along with a significant investment in new construction—a U.S.-led ton-scale search for neutrinoless double beta decay.

We next outline the three broad research thrusts of this subfield as discussed in the introduction.

THE QUEST TO UNDERSTAND THE NATURE OF NEUTRINOS

The properties of the neutrino remain cloaked in mystery because it interacts so weakly. Nevertheless, great progress has been made: it is now known, with the discovery of neutrino oscillations in atmospheric, solar, reactor, and accelerator neutrinos, that neutrinos have mass. The importance of this cannot be overstated: these data contradict a specific prediction of the Standard Model. Not only does neutrino mass disclose physics beyond the Standard Model, but massive

neutrinos may have shaped the largest structures in the universe.

Neutrino oscillations show that neutrinos have mass and set a minimum scale for it. They also provide two scenarios for the mass ordering, or "hierarchy" of the three different states involved, as shown in Figure 5.1. In building the new Standard Model, not only are the absolute masses needed, but it must also be determined if neutrinos are Majorana particles. The Majorana nature of neutrinos would point to super-heavy partners whose decays in the early universe could give rise to the observed matter-antimatter asymmetry (see Sidebar 5.1). Neutrinoless double beta decay provides the most powerful tool to address this profound question. It is perhaps surprising that this type of decay, whereby two neutrons decay to two protons and two electrons without the emission of any neutrinos, can tell us so much about the nature of neutrinos. Nevertheless, the very existence of matter in the universe may be due to this intriguing property of the neutrino. In the following, we elaborate on the nuclear science studies exploring the nature of the neutrino: neutrinoless double beta decay studies, absolute neutrino mass measurements, and other neutrino studies.

Neutrinoless Double Beta Decay

Lepton number, which measures the difference in the number of leptons and antileptons in the universe, is conserved in the Standard Model to within unobservable small quantum fluctuations—though it need not have been. Because of this, every radioactive decay resulting from the weak force should produce both a lepton and an antilepton, according to the Standard Model, thereby keeping the total lepton number of the universe fixed. With the discovery of neutrino mass and mixing, this picture has dramatically changed. A lepton with no electric charge, such as the neutrino, could be its own anti-particle (Majorana particle), and if it has mass, this would unambiguously imply that lepton-number-violating processes are possible in nature. The most powerful way to demonstrate the Majorana nature of neutrinos is by the observation of neutrinoless double beta decay, a nuclear decay in which two electrons but no antineutrinos are emitted, thus explicitly violating lepton-number conservation.
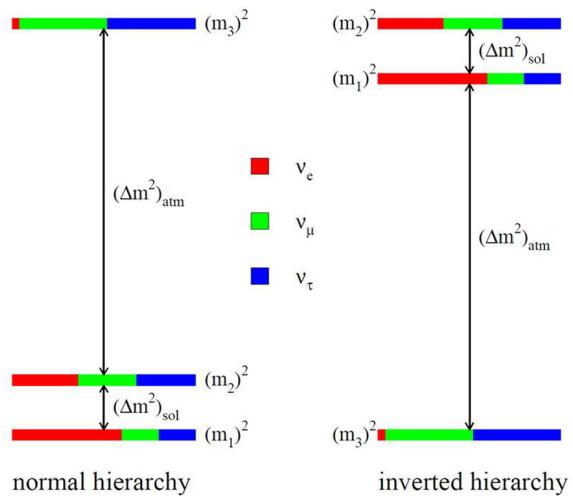
Figure 5.1: *Two possible scenarios exist for the mass ordering, or hierarchy, of the neutrinos. The absolute mass scale (i.e., at what value does the vertical scale begin?) is also not known in either scenario. Initiatives aimed at resolving this open question are discussed in the text.*

The discovery of such a never-before-seen source of total lepton-number violation would provide evidence for one of the key ingredients that could explain the preponderance of matter over antimatter in the visible universe. It would also suggest that the origin of the tiny neutrino masses is qualitatively different from the source of mass for all other known elementary particles. The search for neutrinoless double beta decay thus holds the potential for a major discovery in nuclear physics with profound implications for high energy physics, astrophysics, and cosmology.

The first observation of conventional double beta decay, which preserves lepton number, with the emission of both electrons and antineutrinos was done in a U.S. laboratory in 1987 using ^{82}Se. While such two-neutrino double beta decays have been observed in several nuclei since then, the neutrinoless version has not been detected yet. The discovery of this extremely rare process with a distinctive signature (the sum of the energies of the two decay electrons must match the energy difference between the parent and daughter nuclei) is being actively pursued by teams of nuclear physicists worldwide.

Major technical innovations in recent years have led to a broad range of detector technologies in pursuit of double beta decay, ranging from time projection chambers to semiconductor detectors to bolometers. Indeed, the resulting technical innovations such as the development and fabrication of ultrapure materials, powerful, large-scale cryogenic facilities, novel tracking

devices, and new computing techniques are themselves great achievements (see Sidebar 5.1). Several experiments are currently operational or about to come online with half-life sensitivities for the neutrinoless decay mode in the range of 10^{25}–10^{26} years; they will also provide us with critical guidance about how best to take the next steps.

Next-generation neutrinoless double beta decay experiments have enormous potential to discover this process. With masses of isotope on the scale of tons, expected improvements in half-life sensitivity are two orders of magnitude or more over existing limits (i.e., 10^{27}–10^{28} years). Results from solar, reactor, and atmospheric neutrino oscillation experiments have shown that there must be a neutrino mass state of at least 50 meV. When interpreted within the simplest lepton-number-violating mechanism (i.e., the exchange of light Majorana neutrinos), such "ton-scale" experiments can discover neutrinoless double beta decay if the lightest neutrino mass is above 50 meV or if the spectrum of neutrino masses is "inverted" (see Figure 5.2). Even if neither condition is realized in nature, a discovery is possible if other mechanisms beyond the

simplest one contribute to the decay. Well motivated alternative mechanisms involving new super-heavy particles more than 10 times heavier than weak force carriers (the W and Z particles) provide additional strong motivation for next-generation experiments.

Within the simplest mechanism (light Majorana neutrino exchange), the measurement of the decay half-life of the neutrinoless mode combined with input from nuclear theory allows a determination of the effective neutrino mass. This effective neutrino mass is a special quantum mechanical sum of all of the neutrino masses and is distinct from the individual neutrino masses. In this context, then, the search for neutrinoless double beta decay not only tests the fundamental law of lepton-number conservation but also provides quantitative information about the absolute scale of neutrino mass, complementing direct neutrino mass and cosmological measurements. In combination with these probes, the absence of a signal in the ton-scale search for neutrinoless double beta decay would imply the presence of a Dirac component of the neutrino masses, with significant ramifications for our understanding of the origin of neutrino masses.
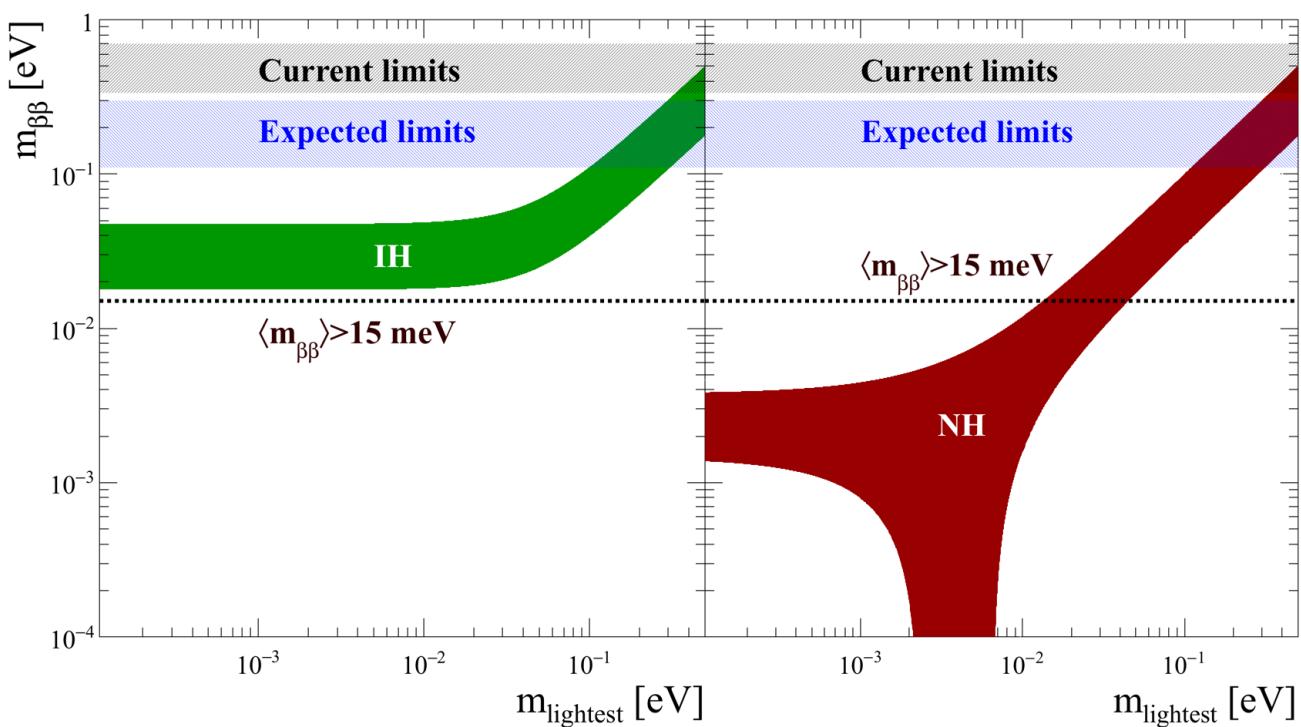
Figure 5.2: *Effective average neutrino mass from neutrinoless double beta decay vs. the mass of the lightest neutrino. Current limits and expected limits from ongoing experiments are shown as gray and blue horizontal bands. The green (for inverted hierarchy) and red (for normal hierarchy) bands show the expected ranges within the light Majorana neutrino exchange mechanism. Next-generation ton-scale experiments aim to probe effective Majorana neutrino masses down to 15 meV, shown as the horizontal dashed line.*

Since neutrinoless double beta decay measurements use the atomic nucleus as a laboratory, nuclear theory is critical in connecting experimental results to the underlying lepton-number violating interactions and parameters through nuclear matrix elements, which account for the strong interactions of neutrons and protons. Currently, there exists about a factor of two uncertainty in the relevant matrix elements, but by the time a ton-scale experiment is ready to take data, we expect reduced uncertainties as a result of the application to this problem of improved methods to solve the nuclear many-body physics.

One of the great experimental challenges is that if this process occurs, it does so extremely rarely (see also Sidebar 5.1). Experiments searching for neutrinoless double beta decay require exceptionally radiopure environments and detector materials to eliminate backgrounds and must be located deep underground to suppress the impact of cosmic radiation. Several experiments and R&D demonstrators are currently under construction or taking data. These experiments will assess the feasibility of the different experimental approaches and demonstrate that the required background reduction can be achieved while continuing to push the limits and sensitivity to neutrinoless double beta decay. With the results from current generation experiments and continued R&D, the optimum path towards building the next-generation detectors will become clear in the next 2–3 years.

U.S. nuclear scientists play leading roles in experiments utilizing various technologies and isotopes of interest. In the U.S. the Enriched Xenon Observatory (EXO-200) is currently operational at WIPP in New Mexico using 3D/time imaging in a liquid ^{136}Xe chamber, while the Majorana Demonstrator at the Sanford laboratory in South Dakota using p-type point-contact ^{76}Ge detectors is about to come on line. The Cryogenic Underground Observatory for Rare Events (CUORE) located at Gran Sasso National Laboratory in Italy is being assembled and commissioned using TeO_2 crystals in a bolometric detector configuration. SNO+ at SNOLAB in Canada is a large-volume, loaded-scintillator detector under construction using ^{130}Te. Other experiments, with some U.S. involvement, using ^{136}Xe are KamLAND-Zen at the Kamioka mine in Japan, NEXT at the Canfranc Laboratory in Spain, and PANDAX-III at the JinPing Laboratory in China. Over the next few years each experiment aims to demonstrate the feasibility and

efficacy of the approach chosen and provide data for planning the next step in the worldwide program.

The realization of a ton-scale neutrinoless double beta decay experiment places stringent criteria on the background reduction and scalability of the chosen technology. While multiple experiments with different isotopes are desirable in a worldwide program of double beta decay searches, each experiment aims for a stand-alone discovery in case of a signal. Several approaches show great promise to be scaled up and are currently being pursued with large U.S. involvement. These include CUPID, an upgrade to the bolometric CUORE detector with isotopic enrichment and added light readout; nEXO, a scaled up version of EXO-200 using a Xe TPC; a Ge experiment based on the combination of the Majorana Demonstrator and GERDA; and a loaded liquid scintillator based on SNO+ with additional Te and improved light collection. KamLAND-Zen is pursuing a similar strategy, SuperNEMO in Europe is investigating a combined tracking and scintillator approach, and investigations are ongoing to add a magnetic field to the NEXT concept.

Future experiments aim to leverage existing investments in the infrastructure and experiment-specific capabilities in the operating underground laboratories such as Gran Sasso, Homestake, and SNOLAB. It is foreseen that the U.S. would mount and lead at least one ton-scale experiment, while different technologies pursued in Europe and Asia would have significant U.S. participation. This is a worldwide effort in which the U.S. should provide leadership as well as foster international cooperation to optimize the program.

A large community of U.S. nuclear physicists will coalesce around the challenge of reaching that goal with whichever experimental approaches emerge from the down-selection process within the next 2–3 years. A possible timeline towards construction of such an experiment is shown in Figure 5.3. The timely start of a ton-scale neutrinoless double beta decay experiment will provide the opportunity to the U.S. nuclear physics community to make a major scientific impact, with implications far beyond the field. It will leverage the investments made over decades and make it possible for the U.S. to maintain leadership in a field with compelling discovery potential.

Ton-scale Neutrinoless Double Beta Decay (0νββ) - A Notional Timeline

Search for Lepton Number Violation

Current generation experiments

NSAC 0νββ decay Subcommittee

R&D: Pre-technology selection

R&D & Project Eng.: Post-technology selection

Ton-scale Construction

Data Taking

| 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |

| Ton-scale Milestones | Mission Decision | Technology Selection | Construction | | | | | | | Data |

Figure 5.3: *Possible timeline for the development of a ton-scale neutrinoless double beta decay experiment.*

Neutrino Mass, Mixing, and Other Puzzles

Neutrino mass can be directly measured via a careful study of the spectrum of electrons emitted in ordinary beta decay. Such measurements are independent of the Majorana nature of the neutrino and are more direct than measurements inferred from studies of the cosmic microwave background radiation. The U.S. has joined Germany and three other nations to build the KATRIN experiment to measure the mass of the neutrino from the beta decay of tritium. This experiment is expected to be complete within the duration of this Long Range Plan. Although KATRIN will be sensitive to masses as small as 0.2 eV, a factor of 10 below current limits, the mass could be smaller still, down to the oscillation limit of 0.02 eV (the smallest possible average mass of the 3 neutrino states). A new idea is being explored, called Project 8, which uses cyclotron radiation to measure the beta spectrum of tritium. The basic concept was successfully demonstrated in 2014.

The neutrino mass hierarchy is one of the key remaining unknowns in the neutrino sector, with important implications for a number of nuclear physics problems. Prospects for answering the open questions of the hierarchy and the possible violation of time-reversal invariance by neutrinos were dramatically advanced in 2012 when experiments using reactor antineutrinos at Chooz in France, Daya Bay in China, and Hanbit (RENO collaboration) in Korea measured the previously unknown neutrino "mixing angle" known as θ_{13}. A number of groups are proposing to use atmospheric neutrinos to determine the mass hierarchy, for example

PINGU in the Antarctic ice cap, leveraging major U.S. investment in IceCube.

The value of the θ_{13} mixing angle has also made it possible to complete designs for the future long-baseline neutrino oscillation experiments. A major U.S. initiative in high energy physics is DUNE, the Deep Underground Neutrino Experiment at the new Sanford Underground Research Facility in South Dakota. The expertise of nuclear theorists will be called on to calculate the interactions of neutrinos with nuclei, using input from several experiments focused on neutrino cross sections.

Improved knowledge of neutrino interactions is also needed at lower energies, for example in the regime of relevance for understanding of supernova neutrinos. Additionally, the elastic scattering of neutrinos from nuclei is expected to be enhanced by quantum mechanical interference effects, but this has never been seen experimentally. New experiments, CENNS and COHERENT, are planned to test this prediction.

Neutrinos from the sun and neutrinos produced by cosmic rays in the earth's atmosphere were the key to the discovery of neutrino oscillations. They continue to provide an unparalleled resource for scientific discovery. Over the past decade the Borexino experiment, a 100-ton liquid scintillation detector located in Italy's Gran Sasso underground laboratory, has detected neutrinos from specific nuclear processes in the sun's core, the pp reaction, the pep reaction, and the decay of ^{7}Be, confirming for the first time explicit predictions

Sidebar 5.1: Going to Extremes: The Quest to Observe Rare Nuclear Decays

Rare event searches are a way to discover paradigm shifts in our understanding of the physical world. The atomic nucleus offers an exquisitely sensitive "laboratory" to search for a hypothesized rare decay process known as neutrinoless double beta decay (0νββ). Observation of 0νββ decay would show that neutrinos are their own antiparticles (Majorana particles) and that the total number of leptons in the universe is not a conserved quantity. The discovery of a lepton-number-violating process would open the door for proposed "leptogenesis" explanations that address the mystery of the matter-antimatter imbalance in the universe.

Many unstable nuclei disintegrate via the beta decay process where a neutron changes into a proton, an electron, and an antineutrino. However, as a consequence of the nuclear pairing force between nucleons, a dozen or so nuclei comprised of even numbers of neutrons and protons cannot undergo beta decay but are candidates to undergo double beta decay. The allowed process of two-neutrino double beta decay (2νββ), where two neutrons simultaneously change into two protons, two electrons, and two antineutrinos, has been observed in many of these nuclei. Double beta decay without neutrino emission (0νββ, see Figure 1)

has not been observed; its discovery would be an unambiguous signature of Majorana neutrinos.

| Standard β Decay | Double β Decay | Neutrinoless Double β Decay |

Figure 1: *Forms of nuclear beta decay.*

The instability of nuclei is characterized by the half-life, defined as the time it takes for ½ of an initial collection of nuclei to disintegrate. Half-lives can range from fractions of a second to billions of years. Searches for 0νββ have set limits on half-lives of $\geq 10^{25}$ years, a whopping million billion times the age of our universe (14 billion years). A half-life of 10^{25} years requires 100 kg of material to detect 1–2 nuclear decays every 10 days. Proposed future ton-scale experiments aim to achieve sensitivities of 10^{27} years, corresponding to observing about five nuclear decays per year in a detector with a *ton* of material. This should be compared to natural radioactivity disintegration rates in a human being (^{40}K, ^{14}C) or a room full of air (^{222}Rn) of thousands per second!

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of astrophysical models of how the sun and other stars make their energy. A new technology based on scintillation in liquid neon shows promise for precise solar neutrino measurements.

A number of existing experiments and anomalies hint at the possible existence of a new "sterile" neutrino, a type of neutrino that does not experience the known weak force. There are, furthermore, some theoretical motivations for eV-scale sterile neutrinos. Numerous experimental proposals to address this question exist, and nuclear physicists play an important role in enabling and interpreting experiments that utilize reactors and radioactive sources.

ELECTRIC DIPOLE MOMENTS

Searches for the permanent EDMs of the neutron and neutral atoms have a long and illustrious history within physics. The EDM of a quantum system is essentially a

separation between positive and negative charges along the system's spin axis. The alignment of EDM and spin signals the breakdown of time-reversal (T) and parity (P) invariance (commonly called "mirror" symmetry), since subjecting the system to T or P transformation leads to a different state (Sidebar 5.2). Equivalently, due to the CPT invariance of quantum field theories, EDMs signal violation of CP invariance, where CP is a combination of the charge conjugation operation (C), which exchanges particles and antiparticles with parity. Such new CP violation could help resolve the question of why there is so much more matter than antimatter in the observable universe.

At the most fundamental level EDMs arise from quantum fluctuations and lack of CP symmetry. Any given particle is not a static entity but constantly emits and reabsorbs all the particles and antiparticles to which it couples, thereby effectively acquiring a charge cloud. If the

Searching for such a rare process has, therefore, required scientists to take extreme measures. Experiments must limit background rates to below the expected signal rate. Detectors are built deep underground to shield the apparatus from cosmic-ray-induced backgrounds and constructed from ultraclean, radiopure materials. A variety of novel discrimination techniques are employed to reject backgrounds and resolve the $0\nu\beta\beta$ signal. A number of experiments worldwide, some led by U.S. scientists, are searching for this elusive decay (see Figure 2).

The Majorana Demonstrator at SURF is deploying pure ^{76}Ge semiconductor detectors to measure the energy deposited by decays of this isotope in an ultrapure electroformed copper refrigerator. EXO-200 at WIPP is operating an ultraclean liquid ^{136}Xe chamber with real-time 3D imaging capability to observe decays of this isotope. CUORE has built one of the world's largest specialized refrigerators, creating the coldest cubic meter in the universe (a hundredth of a degree above absolute zero), to detect the heat deposited by decays of ^{130}Te. SNO+ has an ultraclean thin acrylic shell containing tons of a special light-emitting liquid into which a ^{130}Te compound will be dissolved to look for its decays.

Current generation experiments aim to demonstrate low enough backgrounds and the feasibility of their technical approach to launch a future ton-scale experiment, in which U.S. scientists are poised to play a leading role.

Figure 2: *Searches for neutrinoless double beta decay (clockwise from top left) in the coldest space in the universe (CUORE), the cleanest radiation detectors built to date (Majorana), the deepest neutrino detector (SNO+), and the cleanest operational tracking chamber with 3D/time imaging to date (EXO-200).*

underlying interactions do not respect CP symmetry, the resulting cloud develops a net charge displacement along the spin axis, resulting in the particle acquiring a static EDM. If the CP symmetry breaking arises from new interactions beyond the Standard Model at a large mass scale M, the ensuing EDM scales at $1/M^2$.

Since the pioneering experiment by Ramsey and Purcell in the 1950s, the sensitivity of EDM searches has increased by many orders of magnitude (see Figure 5.4). To date, the three most stringent limits have been obtained for the ^{199}Hg atom, the electron (inferred from an experiment on the ThO molecule), and the neutron. Given the unobservably small contribution to EDMs induced by the Standard Model weak interactions, the current null EDM results and prospective sensitivities have far-reaching implications for fundamental interactions as well as cosmology.
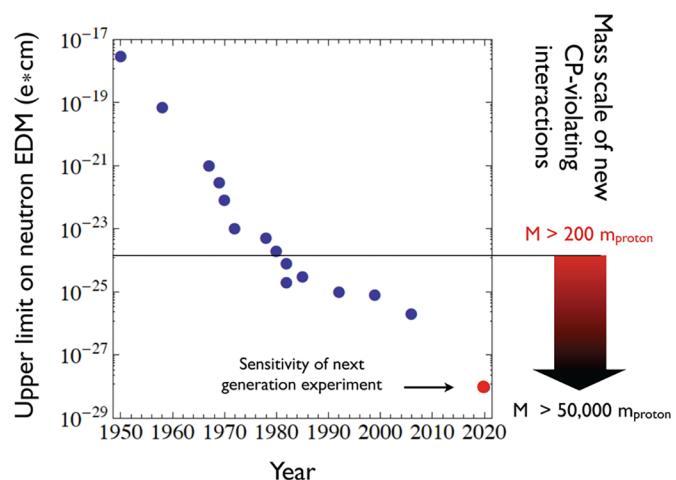
Figure 5.4: *Upper limit of the neutron EDM, which has decreased by a factor of a billion over the 60 years. The corresponding reach in the mass scale of new CP-violating interactions is shown on the right.*

First, previous EDM limits indicate that CP-violating effects in the Standard Model strong interaction are

5. Fundamental Symmetries and Neutrinos

unnaturally small. This has led to the idea of a new symmetry associated with a hypothetical particle—the axion—that could make up part of the nonluminous dark matter in the cosmos.

Moreover, the current results severely constrain new Standard Model candidates that include CP violation at the TeV scale, which is currently being probed in high-energy collisions at the LHC. In fact, EDM limits imply a lower bound of several TeV on the mass scale M associated with new CP violation. Similarly, EDMs at the current level of sensitivity are predicted by theories with more complicated Higgs boson interactions and thus will play a key role in constraining any new model's properties. Finally, and perhaps most remarkably, EDM searches shed light on one of the key questions for all of physics: why the present universe contains more visible matter than antimatter (see Sidebar 5.2). This question has no answer within the Standard Model and requires the presence of new CP violation in the early universe. With the observation of the Higgs boson, it is particularly timely to ask whether the matter-antimatter asymmetry was produced during the electroweak symmetry-breaking epoch that occurred roughly 10 picoseconds after the Big Bang, necessarily involving new particles with masses around or below the TeV scale. If so, then EDM searches provide a particularly powerful probe of the associated CP violation. A remarkable result is that current EDM bounds have squeezed the possibility that the minimal supersymmetric extension of the Standard Model is responsible for the cosmic matter-antimatter asymmetry into a region of parameter space beyond the reach of LHC.

The next-generation EDM searches are poised to improve current sensitivities significantly, opening a path towards major discoveries. Improved sensitivities by a factor of 10–100 would imply reach on the scale of CPV interactions in the 10–50 TeV range, inaccessible at high-energy colliders today and in the foreseeable future. Moreover, next-generation EDM searches will conclusively test the possibility of the supersymmetric origin of matter in the simplest version of the model (see Figure 5.5 and Sidebar 5.3).

The prospect for significant discovery with the next-generation experiments builds on the above considerations and on substantial experimental progress since the 2007 NSAC Long Range Plan. A vibrant program exists in the U.S. and worldwide, with atomic physicists

focused on the electron EDM, while nuclear physicists primarily study the EDM of protons, neutrons, and atomic nuclei. The search for a neutron EDM being developed for the Fundamental Neutron Physics Beamline (FNPB) at the Spallation Neutron Source at Oak Ridge National Laboratory would achieve a hundred-fold improvement in sensitivity. This experiment has demonstrated proof-of-principle following an extensive program of R&D and is presently focused on demonstrating optimal performance for several of the most technically challenging components of the experiment. This R&D and demonstration phase has been and will be taking place at a number of universities and national laboratories, including the UltraCold Neutron facility at Los Alamos National Laboratory. These components are being developed over the next 3–4 years followed by a period of conventional construction to allow data-taking to commence during the timeframe of this Long Range Plan.
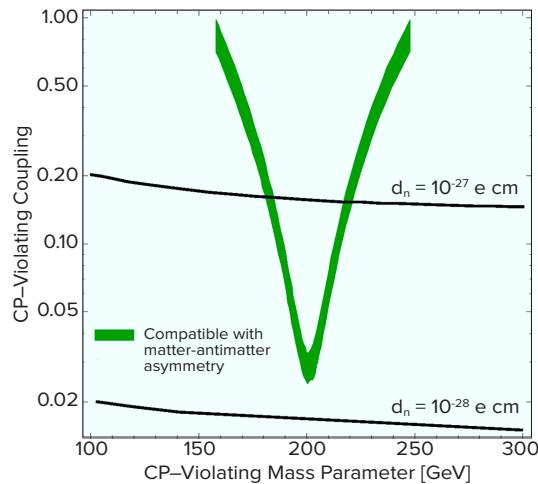
Figure 5.5: *The relationship between the relevant parameters in the minimal Supersymmetric Standard Model that are needed to account for the observed excess of matter over antimatter is shown as the green band. The nearly horizontal lines indicate the size of a neutron EDM as a function of these parameters. The neutron EDM search being developed at the FNPB would probe nearly all of this parameter space.*

Improvements in other EDM systems are also possible for experiments with considerable U.S. participation. A factor of 10 improvement may be achievable for ^{199}Hg and ThO. New efforts are underway by nuclear scientists to search for the EDMs of ^{225}Ra, ^{129}Xe, $^{221/223}$Rn, and Fr, providing probes of new CP violation complementary to those with the existing systems. Looking further into the future, storage ring searches for the EDM of the proton and light nuclei involving U.S. nuclear physicists are under discussion at Fermilab and in Europe and Korea.

Sidebar 5.2: Matter over Antimatter

Why is there more matter than antimatter in the present universe?

This question is one of the most compelling in physics, and its answer is vital to explaining the fundamental origin, evolution, and structure of the nuclear matter that we observe today.

By many accounts, the fireball generated during the Big Bang was democratic: it contained the same number of electrons and quarks (matter) as positrons and antiquarks (antimatter). While it is possible that something gave the Big Bang a slight preference for more matter than antimatter, the subsequent period of cosmic inflation—a brief period of rapid spacetime expansion in the early universe—would have rendered that imbalance imperceptible today. What happened, then, to tip the balance in favor of the matter that makes up nuclei, stars, and life itself?

Physicists do not yet have a definitive answer, but we do know the ingredients for one. According to physicist and Nobel Prize winner Andrei Sakharov, the forces in the early universe must have violated certain fundamental symmetries in ways not seen in the Standard Model. Fundamental symmetry tests in nuclear physics are looking for evidence of such violation, while nuclear theorists are working to relate the results of these tests to the matter-antimatter imbalance.

One of the most powerful probes is the experimental search for an as-yet unseen property of neutrons, protons, electrons, and atoms known as a permanent electric dipole moment, or EDM. As indicated in Figure 1, its discovery would indicate a violation of time-reversal symmetry. In many candidates for the new Standard Model, this violation is intimately connected with the origin of the matter-antimatter imbalance. For example, new supersymmetric, time-reversal-violating interactions would have generated this imbalance about 0.000000001 seconds after the Big Bang, while leaving observable "footprints" today in the guise of permanent EDMs.
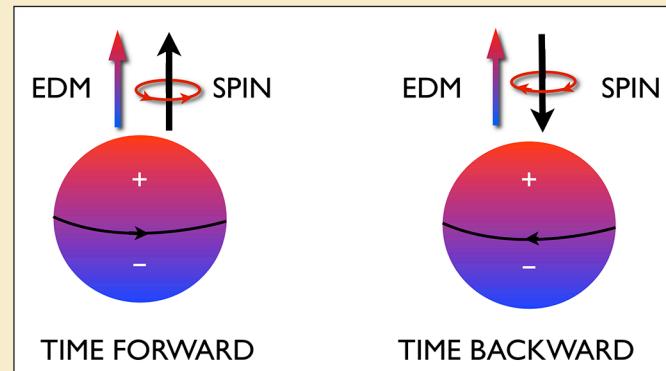
Figure 1: If an EDM is observed, then time-reversal transformation (T) is not a symmetry of nature: it takes a particle with EDM parallel to the spin and transforms it to the same particle with EDM anti-parallel to the spin—a different object that does not exist.

Another powerful probe is the search for the neutrinoless double beta decay of atomic nuclei (see Figure 2 and Sidebar 5.1). The observation of this nuclear decay would immediately imply that neutrinos are their own antiparticles and indicate a never-before-seen breakdown in the balance between leptons and their antiparticles. This symmetry violation would point to the existence of very heavy cousins of today's neutrinos whose decays in the early universe—possibly well before 10 picoseconds after the Big Bang—generated the excess of matter over antimatter.
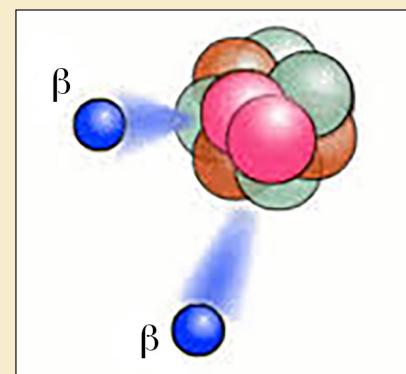
Figure 2: Neutrinoless double beta involves the radioactive decay of a nucleus whereby two electrons are emitted without their usual antineutrino partners.

The observation of a nonzero EDM in any of the above searches would constitute a major discovery with significant implications for the origin of matter and the nature of new forces in the early universe. It would also have implications that go well beyond nuclear physics. Since we do not know where those forces might be hiding, a broad search strategy using a variety of systems is vital. Should a discovery in any one of them be made, results from complementary searches will help us diagnose the detailed nature of the new CP-violating force. In this context, extensive theoretical work is needed to predict the pattern of EDM signatures corresponding to various candidates for the new Standard Model and to compute the resulting matter-antimatter asymmetry. Responding to this challenge, nuclear theorists are pushing state-of-the-art techniques with lattice QCD, effective field theory, many-body methods, and finite-temperature quantum field theory for nonequilibrium environments in the early universe. The prospects are exciting.

FURTHER PROBES OF THE NEW STANDARD MODEL

A great variety of other approaches exist for tests of the Standard Model and searches for new physics. By contrast with the neutrino, the properties of the electron and muon are known to breathtaking precision and serve to sensitively probe the Standard Model. Additionally, copious new sources of cold and ultracold neutrons are beginning to yield important and fundamental measurements of mass and decay properties of this otherwise elusive particle. As described in Sidebar 5.3, ultraprecise weak force measurements involving muons, electrons, neutrons, and nuclei—coupled with accurate theoretical predictions—can provide a unique window on building blocks of the new Standard Model, in many cases exceeding the reach of the LHC. Even if perfect agreement is found, possible Standard Model extensions are severely constrained.

Precision Muon Physics

The muon is a 200 times heavier cousin to the electron. It is typically created in pion decay; the pions are produced using proton accelerators. The muon is unstable, decaying in 2.2 microseconds via the weak force. But this is long enough to form high-intensity beams and also long enough to bring muons to rest in

targets. When muons are born, they are polarized—their spins are aligned—and when they decay, the emitted electron and neutrino energies and directions are highly correlated to the parent muon's spin. These facts are both signatures of violation of parity symmetry, a central feature of the weak force. The muon will continue to serve as a versatile probe in the next few years, as we outline below.

At the Paul Scherrer Institut (PSI) in Switzerland, the muon lifetime was measured by U.S. nuclear physicists to six decimal places; the result defines the strength of the universal weak force, which applies to any and all weak processes. Spectroscopy experiments involving the μ^+e^- muonium atom are testing grounds for the fundamental theory of electromagnetic forces, and they help establish fundamental Standard Model parameters. Studies of μ^-p and μ^-d atoms—where a negative muon replaces an electron—sensitively probe fundamental parameters affected by the strong force such as the proton's charge radius and the weak force strength between muons and protons or between two protons.

The standout effort in this field involves the study of the muon's magnetism, or more specifically, the anomalous part of its magnetic moment, dubbed muon "g-2." The sub-ppm measurement of g-2 at BNL stands 3.6 standard deviations higher than the Standard Model prediction. Might this be a manifestation of the new Standard Model? The 2007 LRP gave high priority to a next-generation muon g-2 experiment, designed with sensitivity to exceed the gold-standard five standard deviation discovery threshold. A unique collaboration between high energy, nuclear, and atomic physicists at Fermilab, this experiment will be completed in the period of this LRP. Numerous U.S. nuclear groups play leading roles. In parallel, there is an intensive theoretical effort to further evaluate the Standard Model prediction at such levels of precision, using LQCD and low-energy, hadronic models. If this deviation is confirmed, it would be truly revolutionary.

Parity-Violating Electron Scattering

Parity-violating electron scattering (PVES) is a powerful technique that exploits the characteristic weak force property (in contrast to the electromagnetic and strong forces): failure to respect parity symmetry. PVES measurements access new physics at and beyond the reach of present day colliders via ultraprecise

measurements of neutral weak forces among electrons and between electrons and quarks inside protons. Recently completed successful experiments focused on measurements of the electron-quark neutral weak force. All PVES measurements are functions of the weak mixing angle θ_W that characterizes electroweak symmetry breaking in the Standard Model. Qweak at JLab, which studied elastic electron-proton scattering and has already accumulated the necessary data, will soon produce the most precise low-energy θ_W determination. The parity-violating deep inelastic scattering (PVDIS) experiment measured the neutral weak force between electrons and individual quarks in a deuterium target.

Significant technical progress, as well as improved theoretical predictions made possible by recent investments, have yielded new opportunities exploiting the energy upgrade of the CEBAF accelerator at JLab. A particularly compelling new initiative known as MOLLER builds on an established tradition at JLab with its exquisitely controlled high-intensity polarized electron beam to study the electron-electron neutral weak force; this can be predicted with negligible theoretical uncertainty. MOLLER, in addition, is sensitive to new types of weak forces thousands of times smaller and has emerged as the only practical method to measure a purely leptonic neutral weak force with sensitivity that goes beyond that in the highest energy electron-positron collisions. Since the last planning period, when MOLLER's physics goals were already endorsed, the initiative has developed into a technically viable proposal, backed by a team of researchers with extensive experience on previous generations of PVES measurements. Launching this measurement within the duration of this LRP is timely as it matches well with measurements with the high luminosity phase of the LHC, anticipated for the early 2020s.

Because of quantum corrections, θ_W varies with the energy scale of the reaction and could be influenced sensitively by non-Standard-Model physics. New projects, SoLID at JLab and P2 at Mainz, Germany, are planned to limit or discover such contributions in a manner complementary to MOLLER and collider experiments. SoLID, whose design also enables a multi-faceted hadron physics program, will measure the variation of θ_W in a regime where a previous experiment, NuTeV, found an unexpected discrepancy. SoLID has unique sensitivity to new quark-quark neutral weak

forces in an energy regime that is challenging to isolate in other PVES and collider experiments. Indeed, model-independent considerations show that the projected sensitivity of all three PVES proposals match, and in some cases exceed, the direct reach of the next phase of the LHC, besides being mutually complementary. It must be noted that a long-term program of atomic parity violation measurements, which is briefly mentioned in the Hadronic Parity Violation subsection has the potential to yield independent θ_W measurements at very low energy.

Precision Neutron and Nuclear Decays

Measurements of the decays of neutrons and nuclei provide the most precise and sensitive characterization of the charge-changing weak force of quarks and are a very sensitive probe of yet undiscovered new forces. In fact, weak decay measurements with an accuracy of 0.1% or better provide a unique probe of new physics at the TeV energy scale, offering discovery potential complementary to muon and electron weak force measurements described above. During the last planning period, significant investments in facilities and experimental techniques are enabling exciting new opportunities. Together with advances in theoretical tools, the priorities for next-generation measurements in this LRP period are clear.

The Nab experiment is being developed at the FNPB at the SNS to measure the neutron decay correlations in the emitted electron and neutrino kinetic energies at the 0.1% level. This experiment should determine the coupling constant that governs the spin-dependent component of the quark charge-changing weak force at the precision and accuracy required to determine one element of the weak quark mixing matrix V_{ud} from neutron decay competitively with spin-independent nuclear decays (see below), as well as establishing competitive constraints on new physics. The UCNA experiment at LANL—the first worldwide to determine the neutron beta decay asymmetry using a source of ultracold neutrons (UCN)—will continue to improve their measurement accuracy and precision; the nominal ultimate cumulative sensitivity goal is 0.2%, an unheard of level not long ago.

Measurements of neutron decay also provide critical input to our understanding of Big Bang Nucleosynthesis predictions for the primordial ^{4}He abundance in the

universe. The envisioned program to perform world-leading measurements of the free neutron half-life involves both cold and UCN neutron sources. Both types of neutron sources are important because they produce different systematic effects in the experiments. Thus, if the results from the two techniques disagree, it is a signal of unaccounted-for systematic effects that must be understood before a precise result can be produced.

The development of a new approach to the measurement of the absolute flux for cold neutron beam experiments has led to a sharpening (now at the four standard deviation level) of the disagreement between the lifetimes extracted from UCN storage and beam experiments. To resolve this issue, improved measurements near the 0.1% level of the neutron half-life in both beam (cold neutrons) and bottled (UCN) experiments are required. The U.S. is in a position to lead efforts using each technique, with cold neutrons at the NIST facility and UCN at the LANSCE facility at Los Alamos.

With nuclei, a decades-long campaign to study numerous "superallowed" spin-independent nuclear weak decays and refined radiative corrections, together with the precise knowledge of the universal weak force strength, yields an impressive precision on V_{ud}, the cornerstone element of the 3-by-3 Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix, at the 0.02% level. The so-called "unitarity test" is thus supported at the few parts per ten-thousand level. This is a spectacular confirmation of the Standard Model led by the dominant contribution determined from low-energy nuclear physics. The result also strongly constrains Standard Model extensions, such as any spin-independent forces. Improving accuracy yet further will require improved theoretical accounting of quantum corrections along with nuclear-structure dependent corrections. The latter can be obtained from detailed analysis of new decays that are mirrors of the decays in the current high precision dataset.

Additional opportunities for high precision measurements involving nuclear beta decays have been identified and are being actively pursued at various national and university laboratories, including the development of the world's strongest source of ^{6}He. This program will enable precision measurements of correlations of decay product directions and energy spectra.

Hadronic Parity Violation

Despite decades of experimental study and theoretical scrutiny, the low-energy weak force of quarks is only partially understood. In particular, significant puzzles remain when strange quarks are involved. The study of parity-violating weak interactions in nuclei could shed new light on these puzzles, revealing whether or not they are specific to the strange quark or a more general feature of the low-energy quark-quark weak force. A tool for studying this is hadronic parity violation, which requires high intensity neutrons and photon sources. The NPDGamma experiment, which measures the asymmetry in polarized neutron capture on protons, completed data collection in the last planning period, and its findings will soon be published. The results, when compared to refined theory, will indicate whether or not there is a long-range weak nuclear force and shed new light on the weak quark-quark interaction. Planned follow-up experiments include neutron capture on ^{3}He at the SNS and a neutron spin rotation experiment at NIST. A potential next-generation initiative is under consideration at the HIγS facility at the Triangle Universities Nuclear Laboratory (TUNL). In parallel, atomic parity violation efforts at several university laboratories and at TRIUMF in Canada are developing new measurements of so-called "nuclear anapole moments" on various isotope chains, which will yield complementary measurements of the nucleon-nucleon neutral weak force.

Dark Photons and Hidden Sectors

A number of nuclear physics facilities are well positioned to mount next-generation searches for new weakly-coupled particles (the "hidden sector"), which are not currently ruled out. These include electron fixed-target experiments at JLab, including HPS, APEX and DarkLight, and BDX. The existence of extremely light particles, as well as possible extra dimensions, is probed by sensitive torsion-balance experiments that explore deviations from Newton's gravity.

EXPERIMENTAL FACILITIES

In the 2007 Long Range Plan, the urgent need for a dedicated deep underground laboratory for neutrino physics and other research was stressed. The site of the Homestake gold mine in Lead, South Dakota, was selected. This is the location where the historic experiment of Ray Davis, who won the Nobel Prize in
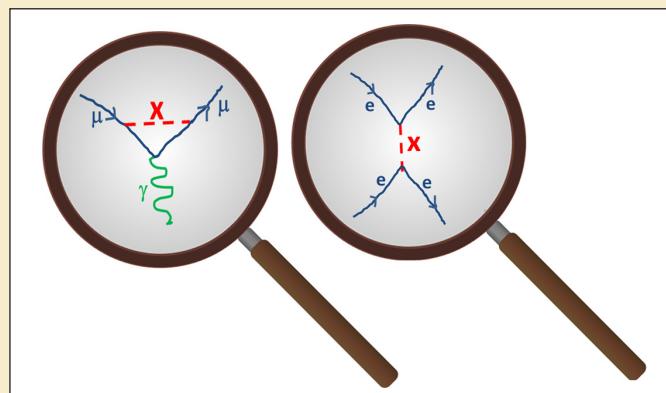
Sidebar 5.3: How Can Precision Measurements Discover the New Standard Model?

Quantum mechanics tells us that a subatomic particle is not static. For example, it tells us that the interior of a proton (see Chapter 2) is not just made of three quarks; close inspection reveals a cloud of quarks, antiquarks, and gluons, all continuously winking into and out of existence. Quarks or leptons can also spontaneously split into a pair of heavier so-called virtual particles that quickly recombine into the original particle. A heavy virtual particle can be emitted only to be "caught" shortly thereafter or passed to another nearby particle. Such fleeting processes seem to violate energy conservation, at least temporarily. The famous Heisenberg uncertainty principle says this is allowed for a brief time interval; how brief depends on the masses of the particles created. These "quantum fluctuations" are happening all the time for each and every particle that exists, producing a wildly diverse quantum soup. Remarkably, their properties can be predicted and often with extraordinary precision. All we need to know are the laws of physics and the complete set of Standard Model building blocks—the particles themselves.

In the late 1940s, measurements of certain energy levels in the hydrogen atom revealed a significant difference from the best theoretical predictions. What was missing was a proper accounting of quantum fluctuations! The Nobel Prize winning work of Feynman, Schwinger, and Tomonaga solved the problem by including these fluctuations in their theory of quantum electrodynamics (QED). Today, QED is the most accurately tested theory in all of physics, but it is not the whole story. We now know that nature's weak and strong forces are similarly affected by virtual particle exchange and quantum fluctuations. In fact, measurements of these "footprints" of the fleeting virtual particles in low-energy processes historically gave the first indication of the existence of the W and Z bosons—the particles that carry the weak force—both with masses ~100 times greater than the proton. While these are now a cornerstone of the Standard Model and are routinely observed at high-energy particle colliders, experimental evidence for their existence first appeared in low-energy measurements.

Today's quest is to discover the ingredients of a larger theory that encompasses the Standard Model but addresses unsolved puzzles. An extraordinarily precise

measurement of the muon's magnetic moment has revealed a significant discrepancy from the Standard Model prediction, pointing to the existence of either new virtual particles that are much heavier than have been seen anywhere else or stealthy ultralight particles. Like the atomic energy level measurements seven decades ago, the muon g-2 measurement may be the harbinger of a new paradigm for fundamental interactions. In a next-generation version of this experiment underway at Fermilab, the muon's spin precession in a magnetic field will be measured to 140 parts per billion, applying an even stronger magnifying lens to the underlying quantum fluctuations (see figure). The prospect of this measurement has also challenged theorists to provide ever more refined predictions within the Standard Model.

Left: A muon (blue) viewed under a powerful magnifying glass while it is interacting inside a magnet (green). The muon's spin can be affected significantly by quantum fluctuations. Right: an electron (blue) viewed similarly while interacting with the intense field of another electron in its vicinity. Here, we spy on muons and electrons briefly emitting, then later "catching" a previously unknown particle of Type X (red). Its fleeting presence will cause the muon's spin to turn a little faster and the electron to experience a slightly weaker or stronger force than the Standard Model predicts, telltale signs of something new.

During the coming decade, new precision measurements in nuclear physics will provide similarly powerful windows on quantum fluctuations. The MOLLER and SoLID experiments at Jefferson Laboratory will exploit the violation of mirror reflection symmetry of weak forces to search for evidence for new forces mediated by cousins of the W and Z particles. Doing so requires measuring tiny parity-violating asymmetries with electron beams. MOLLER, for example, will tease out a predicted asymmetry in beam electrons scattering

off target electrons of 30 parts per billion (ppb) to better than 1 ppb. Studies of the radioactive decays of the neutron and nuclei will reach similar sensitivity. For example, the Nab experiment at the Spallation Neutron Source will determine the directions and energies of neutron decay products to fractions of a percent. Applying the precision magnifying lens to these distinct

processes will provide a more complete picture of what constitutes the new Standard Model, complementing and, in some cases, exceeding the reach of the Large Hadron Collider. Even if perfect agreement with Standard Model predictions is found, by severely constraining the laws of nature, they will leave a lasting impact in textbooks.

physics, was performed. With limited agency funding, supplemented by a substantial commitment from a private donor, new laboratories were constructed at the 4850-foot depth and now house the Majorana Demonstrator double beta decay and LUX dark matter experiments. With the development of the DUNE long-baseline experiment at this location, stewardship has been largely transferred to the DOE Office of High Energy Physics. The deep underground Sanford Underground Research Facility is a new and very significant U.S. facility in the field of fundamental symmetries and neutrinos. Another major facility, the deepest laboratory in the Western Hemisphere, was completed since the last Long Range Plan. SNOLAB in Canada is now the site of several important low-background experiments and could host a new large-scale neutrinoless double beta decay experiment.

Unlike other fields of nuclear physics, there is no central, unifying user facility for experimental work in the field of fundamental symmetries and neutrinos. Instead, this experimental program is distributed at a variety of university and national user facilities and underground laboratories having quite different characteristics. In several instances, these facilities are not operated primarily for nuclear physics research. As a result, because the nuclear physics program has no direct responsibility for supporting expensive facility operations, overall funding in this area is typically quite cost effective. However, because of this situation, the subfield of fundamental symmetries and neutrinos has no intellectual center, or location, where both experimentalists and theorists may interact, develop new ideas, refine existing approaches, and set the direction for the future. The need for such a scientific hub could be addressed through the establishment of a fundamental interactions topical center.

THEORETICAL EFFORT
Progress in nuclear theory is essential for realizing the scientific opportunities with fundamental symmetries, neutrinos, neutrons, and related areas of nuclear astrophysics. Theory interprets the results of experimental measurements in terms of the fundamental questions being addressed by the subfield. Theory generates new ideas for answering those questions, thereby motivating new experimental directions. Theory develops the tools needed to translate these ideas into quantifiable predictions. And theory delineates the broader implications of fundamental symmetry tests and neutrino studies, connecting them with complementary studies at the high energy and cosmic frontiers.

During the last decade, nuclear theorists have developed new tools for computing the cosmic baryon asymmetry and have utilized them to delineate the implications of present and future electric dipole moment searches for the origin of baryonic matter. They have carried out refined computations of nuclear matrix elements for neutrinoless double beta decay, parity-violating asymmetries in electron scattering, the rates for radioactive decays, and the magnetic moments of the muon and neutrinos. And they have developed new ideas for future fundamental symmetry tests, such as the search for electron to tau conversion at an EIC and neutron-antineutron oscillations.

The coming decade presents exciting opportunities for significant theoretical advances. First-principles computations of electric dipole moments of neutrons, protons, and neutral atoms using LQCD and other methods could provide for confrontation between experiment and theory with unprecedented precision. Applying state-of-the-art nuclear structure techniques could significantly reduce the present theoretical uncertainties in the rates for neutrinoless double beta decay. In one of the central problems in physics—identifying the dark matter that dominates our universe—

nuclear physics is needed to characterize and compute the possible nuclear responses in direct-detection experiments and to interpret critically possible indirect astrophysical signals from decaying or annihilating dark matter. In addition, the analysis of new results from the next-generation fundamental symmetries tests and neutrino studies described elsewhere in this chapter could elucidate anticipated results from the high energy and cosmic frontiers.

Realizing these opportunities will require enhancing the theoretical effort in fundamental symmetries and neutrinos. The recent progress has drawn on a relatively modest core of faculty and laboratory scientists whose research focuses on this subfield of nuclear physics. It has also depended on collaborative efforts between this core and a wider network of nuclear theorists in other subfields as well as theoretical colleagues in high energy physics, astrophysics, and cosmology.

Growing this core and fully capitalizing on the synergies with related areas of nuclear theory and other subfields of physics will require a multipronged strategy over the course of the coming decade. Such a strategy should include enhanced research support for individual investigators, providing new opportunities for graduate student and postdoctoral theoretical research in fundamental symmetries and neutrinos, bridge funding for new faculty and laboratory positions, and establishment of a fundamental interactions and neutrinos topical center that brings together the various relevant subfields and stimulates interactions between theory and experiment.

6. Theoretical Nuclear Physics

Nuclear physics is poised for a period of new discoveries made possible by the upgrade and commissioning of state-of-the-art experimental and observational facilities, remarkable advances in high-performance computing, and the relentless pursuit of transformational ideas. A strong interplay between theoretical research, experiment, and advanced computing is essential for realizing the full potential of these discoveries. New measurements drive new theoretical and computational efforts which, in turn, uncover new puzzles that trigger new experiments.

Nuclear theory plays a critical role in defining research priorities for the field and in providing guidance for developing new experimental programs to address them. Further, it provides the framework and flexibility to efficiently respond to the exciting new data emerging from challenging measurements and observations. Most remarkably, theoretical nuclear physics also provides the ability to predict the structure and properties of matter in regimes that are not accessible in the laboratory beyond the current experimental frontier.

Driven by the quest to understand the origin and structure of the visible matter in the universe, research in nuclear theory cuts across all areas of nuclear physics. In addressing complex emergent phenomena across the diverse length scales defining nuclear physics, nuclear theorists have pioneered the development of a variety of powerful techniques that have subsequently found fruitful applications in other areas of science. Beyond the sharing of techniques, nuclear theory provides mutually beneficial connections to atomic physics, condensed matter physics, high energy physics, string theory, astrophysics, and cosmology. Examples of this rich interplay are found throughout this document.

A strong and vibrant nuclear theory effort in the United States is essential to capitalize on opportunities emerging from current and future investments in experimental facilities. Equally important, nuclear theory provides the field with an engine for growth into new directions of discovery. Accomplishing the mission of nuclear physics relies heavily upon a healthy and broad base program in nuclear theory, capable of meeting the challenges of the future with new ideas and a talented next-generation workforce. In this regard, the DOE-supported Institute for Nuclear Theory (INT) plays a

unique and invaluable role by bringing together theorists from across all areas of nuclear physics in a collaborative research environment to participate in community-driven programs that focus on fundamental issues, nurture new ideas, and build bridges to other disciplines.

The community has identified a number of initiatives—requiring critical investments above and beyond the base program—that are needed for the nuclear physics program to succeed during the next decade. In particular, the frontiers of nuclear research will expand dramatically with support of the computational nuclear theory initiative, entailing enhanced access to high-performance computing resources coupled with the development of a diverse workforce trained to utilize them. Moreover, a distributed theory alliance associated with the FRIB facility has been identified as critical for advances in the area of nuclear structure and reactions. Last but not least, multi-institution Topical Collaborations in theoretical nuclear physics have proven to be a successful framework, enabling progress on a number of challenging problems and topical areas. As a result, the following initiatives are identified as critical for the future of the field.

- **We recommend new investments in computational nuclear theory that exploit the U.S. leadership in high-performance computing. These new investments include a timely enhancement of the nuclear physics contribution to SciDAC and complementary efforts and the deployment of the necessary capacity computing.**

- **We recommend the establishment of a national FRIB Theory Alliance. This distributed network will enhance the field through the national FRIB theory fellow program and tenure-track bridge positions at universities and national laboratories across the U.S.**

- **We recommend the expansion of the successful Topical Collaborations initiative to a steady-state level of five Topical Collaborations, each selected by a competitive peer-review process.**

Besides these initiatives, the community endorses undertaking the development and initiation of a strategic plan to address the need for an enhanced theoretical

effort and sustained theory-experiment interactions in the area of fundamental symmetries and neutrinos.

The following sections describe the above initiatives in greater detail and suggest a path forward that will secure a vibrant theoretical nuclear physics effort for the next decade and beyond.

COMPUTATIONAL NUCLEAR THEORY

During the last decade, computational methods have become increasingly prominent in all areas of nuclear physics—including nuclear theory. While analytical techniques remain tremendously powerful for a wide range of problems, they are somewhat limited when trying to understand the properties of strongly interacting systems of quarks, nucleons, or nuclei or electroweak phenomena in complex stellar environments. In this context, computational tools provide a critical path for making further progress. In recent years it has become feasible to numerically explore and simulate environments inaccessible to both experiment and analytical calculations. Examples of such elusive environments include the cores of nucleons, neutron stars, or nuclear reactors; the turbulent birth of a supernova; and the properties of hot quark-gluon plasma. Along with experiment and theory, computation is now recognized as the third pillar supporting the field of nuclear physics.

Our understanding of the frontiers in nuclear physics research will expand dramatically with increased access to high-performance computing resources, coupled with a diverse workforce trained to utilize them. In the coming decade, sustained investment in these areas will enable an era of nuclear physics where theoretical efforts are unified through computational methods. Importantly, high-performance computing is essential to the success of many key components of the present and future experimental programs. By aligning nuclear physicists with computational scientists, the DOE-sponsored SciDAC program has enabled significant advances in computational nuclear physics in the past decade. The algorithmic advances and highly optimized codes that SciDAC has facilitated have been key to the leveraging of substantial leadership-class computational resources. SciDAC programs have brought together a large fraction of the nuclear theory community and represent a significant increase in support for junior scientists. This was possible only through a tremendous leveraging of

the base programs in DOE's Offices of Nuclear Physics, High Energy Physics, and ASCR, as well as strong support from NNSA.

A range of computational resources is required to optimize scientific productivity. Capability computational resources are used to perform calculations that require the maximum computer power, often involving hundreds of thousands of compute cores. In contrast, mid-scale capacity resources are used for medium-sized calculations that are performed many times. Nuclear theorists require both types of resources.

Collaborations of nuclear theorists acquire access to the largest capability computational resources provided by ASCR through peer-reviewed proposals submitted to the DOE or the NSF, which compete with all fields of science, engineering, medicine, and business. The fraction of the national capability resources acquired by nuclear theory has remained approximately constant during the last few years, and it is critical that this continues or increases in the future. The DOE provides capacity computing resources through proposals submitted to NERSC or through the U.S. Lattice QCD Consortium (USQCD) hardware project, but these resources have diminished, despite an increased need. In order to accomplish the computational goals of the nuclear theory program and to fully exploit the current and next generation of leadership-class computational resources, it is critical for nuclear physicists to have significantly greater access to capacity computing resources.

The last decade has witnessed the growth and evolution of computational hardware architectures. There are presently two distinct machine architectures on track to deliver exascale computing, both of which are distinguished by increased hardware complexity and a need for machine-specific software optimization. With pre-exascale machines being deployed in 2017–2018, it is essential that the nuclear theory community be prepared to exploit these new architectures, requiring a concerted effort to port scientific codes and to optimize their performance. A significant software development workforce and close collaboration with computer scientists, applied mathematicians, and hardware vendors are required to successfully port our existing scientific code bases, in addition to expanding their scientific reach.

High-performance computing is poised to deliver the field of nuclear theory into an era where predictive capability will be typical and where quantities will be theoretically determined with a complete quantification of all associated uncertainties. This era will bring with it answers to long-standing nuclear physics questions that impact fundamental science and help address our Nation's security and energy needs. Investment in high-performance computing resources and increased funding to support workforce development in this area are critical to the United States maintaining its forefront position in nuclear physics research.

THE INT AND NUCLEAR THEORY EFFORTS AT LARGE FACILITIES

The DOE-supported INT plays a unique role in our community, overarching all subareas of nuclear theory and making fruitful connections with other fields. Through its community-driven workshops and programs, it provides a collaborative research environment where visiting scientists focus on fundamental issues in nuclear physics and form bridges to other disciplines. Further, it provides a forum to bring theorists and experimentalists together to dissect and understand current experimental observations. INT programs have helped germinate ideas as diverse as the No-Core Shell Model, Nuclear Effective Field Theory, Color Glass Condensates, and Generalized Parton Distribution Functions. The INT hosts in excess of 400 scientists per year and has played a critical role in training leaders in the field with its postdoctoral and fellow programs. Indeed, a large fraction of INT postdocs and fellows are now tenured or in tenure-track positions and have been the recipients of DOE or NSF Early Career Awards. The INT hosts the University of Washington REU program and continues to administer the National Nuclear Physics Summer School.

Successful experimental programs are tightly inter-woven with advances in theory. Theorists provide critical guidance in planning and interpreting measurements performed at the experimental facilities. Theory efforts at national user facilities, working closely with experimentalists, continue to serve as focal points for facilitating interactions on topics relevant to the current and future experimental programs. Over the last few decades, two large nuclear physics user facilities have been constructed, namely CEBAF at Jefferson Lab and RHIC at Brookhaven National Lab. These facilities have enabled outstanding discoveries and, in both cases,

theory efforts strongly coupled to the facility were put in place. Although based on different paradigms, the DOE-supported Jefferson Lab and BNL nuclear theory efforts, as well as the independent effort of the RIKEN-BNL Research Center, are internationally recognized as having made critical contributions to the success of the associated experimental facilities. They build scientific bridges to wider theory communities and have created synergy with initiatives such as bridge/joint faculty positions and postdoctoral fellows, providing for the future of the field. They serve as the natural channel for advice on the scientific merit and planning of experimental programs. Continued support for these efforts is critical.

Before FRIB comes online, it is essential to ensure that a strong theory initiative is put in place to enable the success of the experimental program. In the spring of 2013, a national steering committee was put together, formed of 13 senior members of the low- energy nuclear physics community. The goal of the committee was to analyze the required ingredients for a future FRIB theory initiative, including ramp-up funding options and an appropriate organizational structure, and then to work with the agencies to develop a realistic path forward. The steering committee met regularly for one year, took community input at the low-energy users meetings, and consulted with DOE throughout the process. The steering committee studied the models associated with both JLab and RHIC and identified common elements as well as differences in the implementation. The result of this planning process is a proposal that differs from both the JLab and the RHIC models. The proposal is for a distributed FRIB Theory Alliance, a theory effort involving many institutions throughout the country and tightly coupled to experiment. This theory alliance will enhance the field through two new initiatives: (i) the national FRIB theory fellow program and (ii) the FRIB tenure-track bridge program. The full establishment of the FRIB Theory Alliance is critical to the success of FRIB.

TOPICAL COLLABORATIONS

Many aspects of theoretical nuclear physics can benefit from additional long-term, sustained efforts beyond the base program that bring together the resources of several institutions in a coordinated way to address a well-defined problem or topical area with a clear set of deliverables. Following the recommendation from the 2007 Long Range Plan and with these goals in

mind, the DOE established for the first time in 2010 three Topical Collaborations. As envisioned, each of these collaborations has functioned as a hub of a network of scientists from the participating institutions. Organized around identified challenges, each Topical Collaboration has brought together a critical mass of researchers from diverse institutions with disparate experience and techniques in the service of achieving common goals that none could have achieved separately. They have fostered collaborations across traditionally distinct subfields in nuclear theory to address exciting opportunities. They have created and sustained interaction and communication within their networks in many ways, including summer schools and workshops, and in so doing have energized the research of their members and of many postdocs and students. *Six new tenure-track faculty members in theoretical nuclear physics have been hired as part of the topical collaboration effort*. In all these ways, in addition to their impressive science accomplishments, these three Topical Collaborations have made lasting, positive impacts on the field of nuclear science. The DOE should be commended for having inaugurated this new mode of supporting research.

The science accomplishments of the three Topical Collaborations are integral components of the progress in nuclear physics since the last Long Range Plan and, as such, are described within the relevant science sections. For example, see Chapter 4 for how the "Neutrinos and Nucleosynthesis" Topical Collaboration has exploited the opportunities presented by newly discovered neutrino properties and state-of-the-art supercomputing technology to discover new aspects of collective neutrino flavor oscillations in astrophysical environments, including their relation to heavy element nucleosynthesis. In turn, important developments in reaction theory achieved by the "Theory of Reactions for Unstable Isotopes" Topical Collaboration have significantly advanced our understanding of reactions in which a deuteron transfers its neutron to a heavy

nucleus, an effort that is critical for extracting neutron-capture rates for r-process nucleosynthesis from future FRIB data (see Chapter 3). And, the "Jet and Electromagnetic Tomography" Topical Collaboration has built a theoretical framework with which they have calculated the dynamics of an expanding droplet of quark-gluon plasma and the loss of energy experienced by a high-energy quark propagating through it. In doing so, they have determined key properties of quark-gluon plasma as described in Chapter 2. Each of these impressive achievements was made possible by a Topical Collaboration bringing together diverse groups of people with the necessary expertise to work towards a common goal.

At the time the first Topical Collaborations were selected, there were many other strong proposals whose funding would have further enhanced the field. Looking at the impressive successes of the three Topical Collaborations that were launched in 2010 (see Sidebar 6.1), it is apparent that there are still many opportunities for advances in nuclear science that could have been realized if Topical Collaborations targeted in further directions had been launched between then and now. Groups supported by the base program have, of course, pursued fruitful research agendas; what has gone unrealized are the opportunities for cohesion, for synthesis, for weaving together otherwise separate strands of expertise in the many cases where such synergy was needed to make substantial progress. A healthy base program must come first since, without it, the strands that a Topical Collaboration weaves together would not be available. What Topical Collaborations provide is additional theoretical nuclear physics capabilities that the base program, by itself, cannot provide, making it possible for scientists at different institutions in possession of different pieces of a single puzzle to come together and create a new and more compelling picture.

Sidebar 6.1: Topical Collaborations: An Instant Success Story

What do the hottest liquid in the universe, the stealthy neutrino, and nuclei at the limits of stability have in common? They were each at the center of one of the first three *Topical Collaborations* that the field identified in the 2007 Long Range Plan as the highest priority for new investments in nuclear theory. Each multi-institutional topical collaboration has brought together a network of nuclear theorists with diverse expertise working towards a common scientific goal.

Also essential, each topical collaboration created and fostered a community of young theorists involved in both cutting-edge theory and high-performance computing. By 2010 the DOE had established three topical collaborations and by 2015 all three have delivered on their promise. They have also enhanced the permanent workforce in nuclear theory, contributing to the hiring of six new tenure-track faculty members. By any measure, the Topical Collaborations initiative is a rousing success.

Figure 1: *Carla Fröhlich (North Carolina State University) and Paul Romatschke (University of Colorado) are two of the six new faculty that were added to the national workforce in nuclear theory as a result of the Topical Collaborations.*

The aim of the Topical Collaboration on Jet and Electromagnetic Tomography (JET) was to address a set of well-defined problems within the theory of jet quenching in relativistic heavy-ion collisions (see Figure 2.12 for an example of a jet-quenching event at the LHC). As energetic heavy ions collide, jets are copiously produced from the violent collisions between the incoming quarks and gluons and are ultimately detected as a characteristic spray of particles. By assembling a network of theorists in close collaboration with experimentalists, the JET Collaboration has delivered on its promise. It extended the theoretical framework for jet interactions with the nuclear medium beyond previously-made approximations. This provided

a critical step towards the goal of using jet quenching as a quantitative tool to study the properties of QGP. In turn, theoretical uncertainties were reduced to a degree that essential characteristics of the QGP produced in RHIC and LHC collisions could be reliably deduced from the experimental data. The approach and tools developed—and made publicly available—will enable future precision studies of QGP properties.

The Topical Collaboration on Neutrinos and Nucleosynthesis in Hot and Dense Matter (NuN) focused on three interrelated fundamental questions: How and where are the heavy elements in the universe synthesized? What role do neutrinos play in stellar explosions and nucleosynthesis? And what are the states of matter at high density and temperature realized in neutron stars and supernova? By developing new techniques to solve the many-nucleon and many-neutrino quantum systems over a wide range of extreme ambient conditions, the NuN collaboration was able to (1) connect experimentally accessible nuclear properties to those encountered in astrophysical compact objects, (2) address how neutrinos emerging from the hot neutron stars can impact nucleosynthesis, and (3) address how key properties of dense matter leave their imprint on neutrino and X-ray emission from supernova and neutron stars.
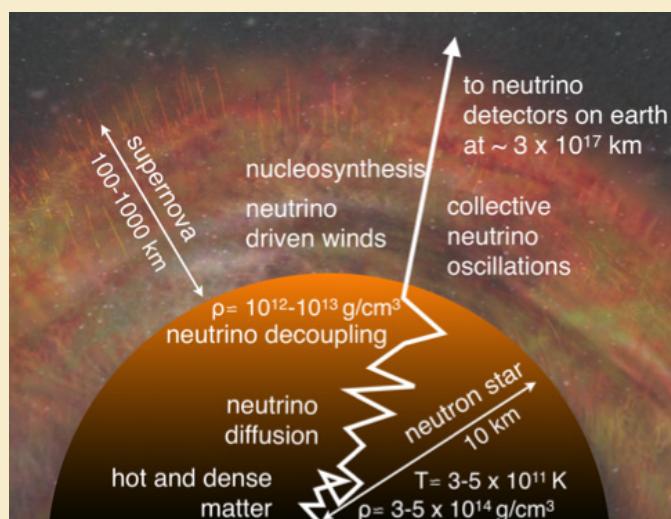
Figure 2: *Calculations of neutrino interactions at high density and collective neutrino flavor oscillations by the NuN collaboration have provided new insights into heavy element nucleosynthesis in astrophysical environments.*

The mission of the Topical Collaboration on the Theory of Reactions for Unstable Isotopes (TORUS) was to develop new methods to advance nuclear reaction theory for unstable isotopes—particularly the (d,p) reaction in which a deuteron, composed of a proton and a neutron, transfers its neutron to an unstable nucleus. After benchmarking the state-of-the-art theories, the TORUS collaboration found that there were no exact methods to study (d,p) reactions involving heavy targets, the difficulty arising from the long-range nature of the well-known, yet subtle, Coulomb force. To overcome this challenge, the TORUS collaboration developed a new theory where the complexity of treating the long-range Coulomb interaction is shifted to the calculation of so-called "form-factors." An efficient implementation for the computation of these form factors was a major achievement of the TORUS collaboration. All the new machinery developed will soon be applied to (d,p) reactions involving heavy nuclei relevant for astrophysics, energy production, and stockpile stewardship.

ATTRACTING AND TRAINING THE NEXT GENERATION

The nuclear theory community plays an essential role in attracting, training, and retaining the bright young minds that will shape the course of nuclear physics in the coming decade. As articulated in Chapter 8, Workforce Development, Education, and Outreach in Nuclear Science, graduate education is at the heart of educational activities in nuclear science. Beyond the standard university-based programs, students are trained in forefront areas of nuclear physics through participation in workshops and schools. In this context, the National Nuclear Physics Summer School has emerged as a vital complement to single-institution training. Enhancing the breadth and depth of the nuclear science training that our field provides its graduate students through these programs will play a key role in their many subsequent critical contributions to our Nation and our field.

Yet, it has become clear that in order to prepare our graduate students to face the current and future challenges of our field, we need to go beyond the summer school structure and offer an additional venue that enables even more technical depth. The nuclear theory community has demonstrated its leadership in student training by introducing a joint North American and European venture for Training in Advanced Low-Energy Nuclear Theory (TALENT). TALENT is a self-organized project with the goal of delivering a coherent graduate curriculum that will provide the foundation for a low-energy nuclear theory research program, linking modern theoretical and computational approaches with ongoing experimental efforts. By the end of 2015, TALENT will have executed eight out of the nine courses originally proposed. Major challenges are coordination and sustainability. In this regard, the proposed FRIB Theory Alliance intends to work with universities to develop a model for transferring academic credit, with the goal of these courses becoming part of the academic curricula of the participating institutions. This theory alliance also intends to provide a repository for the educational material, including software that will be developed. This initiative may serve as a model for other fields.

In the last decade, nuclear theory has been extremely successful in attracting exceptionally talented junior scientists into the field. This unique talent has been recognized by the funding agencies through a large fraction of prestigious awards. Since DOE instituted the Early Career Award in 2010, nuclear physics has received over 10% of the Office of Science awards, with slightly more than 40% of those awarded to theory. The NSF CAREER award spans all fields of science, and in the years from 2007 to 2014 five out of a total of nine nuclear physics awardees were theorists.

The community strongly supports continuing these prestigious awards and will continue to make every effort to attract, train, and retain young talent to ensure that it is well prepared to address the exciting scientific challenges that lie ahead.

7. Facilities and Tools

Forefront research requires forefront tools. The ever-increasing technical challenges faced by contemporary nuclear physics experiments and nuclear theory calculations drive innovation in the design and engineering of accelerators, detectors, electronics, computer hardware, and software. These innovations, in turn, advance technologies adapted to serve societal needs in fields ranging from cancer therapy (see Sidebar 7.1), to medical imaging and medical radioisotope production, to homeland security, and to general high-performance computing. A number of important innovations have arisen from basic nuclear science research during the past decade, both in the U.S. and abroad. The research described in this document is a truly international endeavor, with many foreign users of U.S. facilities and significant U.S. participation at foreign facilities. This chapter briefly describes the array of tools currently available, major new tools needed to carry out research proposed herein, and a few of the technical innovations our research has recently stimulated (see Sidebar 7.2).

INTRODUCTION TO U.S. CAPABILITIES

The four major components of the U.S. basic nuclear research portfolio deal with (1) the roles of quarks and gluons in all forms of nuclear matter, (2) the structure of all nuclei, (3) their roles in astrophysical processes, and (4) the uses of nucleons and nuclei to elucidate nature's adherence to fundamental symmetry principles and the properties and interactions of neutrinos. Each of these four subfields is served by its own unique U.S.-based facilities.

The U.S. boasts two world-leading and complementary superconducting accelerator facilities for research related to QCD aspects. Both have undergone substantial accelerator upgrades pursuant to the 2007 Long Range Plan and are now proposing specific detector upgrades needed to realize the full scientific potential of the enhanced facilities. CEBAF at JLab is the most powerful facility of its kind in the world, providing multi-GeV electron beams bombarding stationary nuclear targets for a precision probe of "cold" nuclear matter (i.e., individual nucleons and nuclei in their ground state or low-lying excited states). Its world-leading capabilities facilitate unique investigations of nucleon structure in the regime of valence quarks, short-range correlations between nucleons inside nuclei, and aspects of parity

violation in the electromagnetic interaction. Its nearly completed major upgrade raises the beam energy from 6 to 12 GeV and advances the detector instrumentation, significantly extending the scientific reach of its program.

The RHIC at BNL is the only operating collider facility in the U.S. and the most versatile collider in the world. Its primary research program focuses on studying "hot" nuclear matter created in a microcosm by colliding heavy nuclei at nearly light speed in its intersecting superconducting rings. Such collisions produce microscopic bits of matter at the extreme temperatures of the infant universe during its first microseconds of existence, before quarks and gluons cooled enough to condense into protons and neutrons. The unique properties of this matter are inferred by tracking thousands of particles emerging from each collision in two large, multifaceted collider detectors. RHIC's extreme versatility in collision energy and beam species extends its science program, including a secondary program of polarized proton collisions to illuminate the internal spin structure of the proton, and provides capabilities not available at the LHC at CERN in Europe.

Some aspects of the quark structure of nucleons are more directly studied using neutrino and hadron beams at Fermilab, whose operations are supported by the High Energy Physics Office of DOE. But the current suite of U.S. and worldwide accelerator facilities does not yet provide all the capabilities needed to complete our understanding of the QCD structure of nuclear matter. As detailed elsewhere in this report, many current investigations point to the missing link being a polarized, high-luminosity EIC, where physicists can probe nucleons and nuclei in a regime where their properties are dominated by abundant gluons. The proposed new facility is described in more detail later in this chapter.

During the period covered by the 2015 Long Range Plan, the centerpiece of U.S. capabilities for research on nuclear structure and nuclear astrophysics will become the FRIB, currently under construction at Michigan State University (MSU). FRIB will accelerate beams of nuclei as heavy as uranium in a high power superconducting linear accelerator and allow those beams to interact with thin production targets. Short-lived exotic nuclei produced in those interactions can then be used in flight, or stopped and reaccelerated, providing world-leading

capabilities to explore the limits of nuclear existence and the rates of nuclear reactions near those limits that are related to the astrophysical origins of heavy elements in the universe. While awaiting FRIB completion, the U.S. community of nuclear structure and astrophysics experimentalists utilizes a spectrum of other facilities, ranging from national user facilities at Argonne National Laboratory (ATLAS) and MSU (the NSF-funded NSCL) to key smaller, university-based laboratories providing beams of both stable and short-lived nuclei.

Research on fundamental symmetries and neutrinos utilizes the most diverse array of facilities. Some of the research requires beams from accelerator facilities while other experiments search for rare events from natural sources in deep underground sites, shielded against cosmic-ray backgrounds.

Fundamental properties of the neutron and of the weak interaction responsible for its radioactive decay are investigated primarily at three U.S. facilities: the Fundamental Neutron Physics Beam Line (FNPB) at the Spallation Neutron Source at Oak Ridge National Laboratory; the ultracold neutron (UCN) source at the Los Alamos Neutron Science Center (LANSCE); and the fundamental neutron physics facilities at the NIST Center for Neutron Research. Other experiments studying aspects of fundamental interactions utilize secondary beams of neutrinos or muons produced at Fermilab. A prominent part of the CEBAF program adapts parity-violating electron scattering to probe fundamental aspects of the weak interaction. The trapping of heavy radioactive nuclei produced at FRIB will facilitate novel searches for time-reversal violation.

Deep underground laboratories providing the shielding needed for rare event searches are available at a number of mine or tunnel sites around the world. The most prominent U.S. underground laboratory is the Sanford Underground Research Facility (SURF), operated by the South Dakota Science and Technology Authority with partial funding from DOE. Among other experiments, it now hosts one of the current generation searches for neutrinoless double beta decay, the Majorana Demonstrator.

Such searches for extremely rare phenomena of extremely high scientific impact also demand significant advances in the sophistication of detector instrumentation. Two particular developments along this line are highlighted in this report and briefly described in this chapter: the state-of-the-art cryogenic systems and magnetic field uniformity needed to improve the sensitivity to a time-reversal-violating neutron electric dipole moment by two orders of magnitude, and the ultralow background demands of a ton-scale search for the lepton-number-violating process of neutrinoless double beta decay.

MAJOR U.S. ACCELERATOR FACILITIES AND THEIR DETECTORS

High-Energy Nuclear Physics/QCD Facilities

CEBAF: The 12-GeV Upgrade
CEBAF features continuous wave electron beams of extremely high quality—small spatial extent and energy spread, high intensity and beam polarization, 100% duty factor—delivered to a variety of targets (including polarized targets), spectrometers, and advanced detectors. The 12-GeV Upgrade of the CEBAF will provide new capabilities to address quantitatively the nature of confinement and the structure of hadrons comprised of light quarks and gluons. Together these will allow both the spectrum and the valence structure of hadrons to be elucidated in unprecedented detail. The upgraded facility will also enable experimental studies of fundamental short-distance properties in nuclei, which will provide a quantitative understanding of nuclear properties and their relation to the distribution of quarks in nuclei. Furthermore, the development of extremely high-intensity, highly-polarized, and extraordinarily stable beams of electrons provides innovative opportunities for probing (and extending) the Standard Model, both through parity-violation studies and searches for new particles. The doubling of CEBAF's energy from 6 GeV to 12 GeV has been completed, and CEBAF has started its initial science operations in Halls A and D, which houses the new GlueX facility. Construction of major new equipment in Halls B and C, CLAS12 and the Super-High Momentum Spectrometer (SHMS), respectively, remains ongoing and is anticipated to be completed by 2017. This would complete this DOE-funded 12-GeV Upgrade project.

Detectors for Hadron Physics
The 12-GeV CEBAF is accompanied by new detector upgrades. The initial science program in Hall A makes use of both the existing High Resolution Spectrometers

and the Super-BigBite Spectrometer (SBS), presently under construction, for a program of complementary high-luminosity nuclear structure studies and nucleon form factor studies. The upgraded Hall B spectrometer, CLAS12, will be suited in particular for understanding nucleon structure via generalized parton distributions and for studying propagation of light quarks in cold nuclear matter. These measurements require detection of several final state particles and good missing-mass resolution or observation of exclusive final states, accomplished by the very large acceptance of the Hall B multiparticle spectrometer. In Hall C the coincidence magnetic spectrometer setup of the HMS and the new SHMS supports high luminosity experiments detecting reaction products with momenta up to the full beam energy, a virtue well matched for conducting precision studies of the valence quarks in nucleons and nuclei. The new Hall D and its dedicated spectrometer, the GlueX facility, are designed to search for QCD-predicted hybrid mesons produced with linearly polarized photons. GlueX data will enable a partial wave analysis of any new observed mesons to determine whether they have "exotic" quantum numbers, forbidden for simple quark-antiquark states. The spectrometer can also perform studies of meson and baryon spectroscopy.

While the currently envisioned program includes both high rate capability and large acceptance devices, there is no single device that is capable of handling high luminosity (10^{36}–10^{39} cm^{-2}s^{-1}) over a large acceptance as needed to fully exploit the 12-GeV Upgrade. The SoLID (Solenoidal Large Intensity Device) program is designed to fulfill this need. SoLID is made possible by developments in both detector technology as well as simulation accuracy and detail that were not available in the early stages of planning for the 12-GeV program. The spectrometer is designed with a unique capability for reconfiguration in order to optimize capabilities for either PVDIS or semi-inclusive deep inelastic scattering (SIDIS) and threshold production of the J/Ψ meson. Recent years have also seen proposal development for the MOLLER experiment, which would perform high precision tests of the Standard Model in parity-violating electron-electron scattering. Such an experiment offers a unique complement to the capabilities of the upgraded LHC and, thereby, adds enormously to the physics reach and impact of the 12-GeV CEBAF.

The capabilities of these large scale major instruments are augmented in important ways by ongoing or proposed smaller scale upgrades: ring-imaging Cherenkov (RICH) detectors to provide kaon identification in two sectors of CLAS12; a direct-imaging Cherenkov detector for GlueX to identify kaon decay daughters of hybrid mesons; electromagnetic calorimeters to provide neutral particle detection (NPS) in Hall C and to facilitate rare meson decay studies in Hall D; upgrades to provide detection of backward-going nucleons arising, for example, from short-range nucleon-nucleon interactions inside nuclei. The whole is often more than the sum of its parts: Hall A with SBS and the proposed SoLID, Hall B with CLAS12 enhanced by the new RICH detectors, and Hall C with HMS-SHMS supplemented by NPS will all allow far more refined high-resolution imaging of the nucleon's internal landscape than could ever be done by each device separately.

Complementary studies of hadronic interactions using neutrinos and of the antiquark content in nucleons via high statistics studies of Drell-Yan processes can be carried out at Fermilab.

RHIC
The RHIC at BNL is complementary to the heavy-ion program at the CERN LHC in Europe; both machines are required to investigate how critical QGP properties emerge and change with temperature (i.e., beam energy) and resolving power. While LHC excels in the high-energy frontier, it is not well suited to investigate the crucial transition region between QGP and ordinary matter, where some of the most interesting phenomena appear. Recent upgrades to the RHIC accelerator include a new electron beam ion source (EBIS), which provides a wide variety of ion beams up to uranium nuclei, and the development of stochastic cooling for bunched beams, which has allowed high-energy heavy-ion collision rates exceeding the original design value by a factor of 20. Other noteworthy aspects of RHIC's extreme versatility in collision energy and beam species are (1) the capability to vary the collision energy over more than a factor of 20; (2) the capability to collide very asymmetric beam species; and (3) the capability to collide beams of polarized protons, making RHIC the only polarized proton collider in the world. A planned new enhancement would introduce electron cooling of the heavy-ion beams at the low end of RHIC's energy

Sidebar 7.1: Nuclear Scientists Lead the Way on Proton Radiation Therapy

The tools and results of basic research in nuclear science, coupled with research into the chemical properties of radioactive nuclear isotopes, have become, over the last decade, essential ingredients of any modern healthcare strategy for diagnosing and treating disease, particularly in the area of oncology. In the U.S. and other developed nations, cancer is the second leading cause of death. Half of the U.S. cancer patients receive radiation treatment, most with external beams.

Proton beam therapy is widely recognized as the most effective external beam method in the selective destruction of cancer cells for certain tumors. The goal in radiation therapy is to deliver lethal doses to the tumor while minimizing or eliminating normal tissue injury for often close-by critical organs. Because charged particles deposit most of their energy, or dose, in a narrow range, called the Bragg peak, radiotherapy with energetic protons (<250 MeV) realizes this goal by allowing oncologists to design fine-tuned 3D treatment plans. In 2007 there were seven proton therapy centers in clinical operation in North America. At the end of 2014 there were 18, with 17 more in either construction or planning phase (see Figure 1).

Particle therapy facilities in operation in 2007

Particle therapy facilities in operation in 2014

Particle therapy facilities under construction or in planning stage
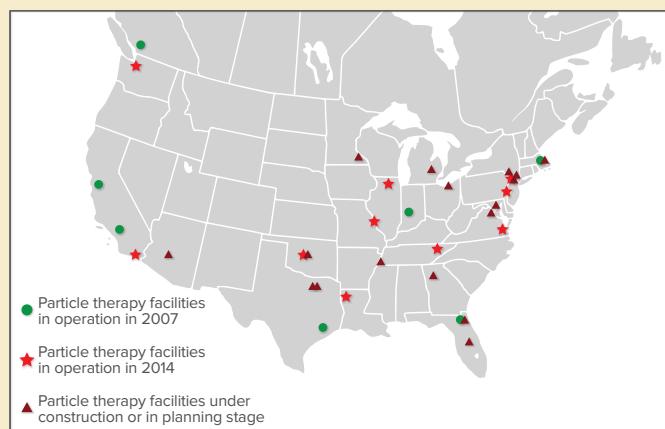
Figure 1: *The growth of proton radiation therapy centers in North America since 2007 (figure from www.ptcog.ch).*

Proton therapy centers are an alliance of applied nuclear science and medicine. Behind the scenes of the treatment rooms that patients are most familiar with are proton accelerators and beam lines with multiple elements to focus and steer the beam for treatments. Nuclear scientists have been key to the concept, design, construction, and operation of these centers. For

example, four of the newer U.S. centers were developed by a company founded by John Cameron, based on his nuclear science experience and employing a number of staff that helped convert the Indiana University Cyclotron Facility into the Midwest Proton Radiotherapy Institute. One of the two largest centers in the world, the Hampton University Proton Therapy Institute, was established with Cynthia Keppel, a joint JLab/Hampton University nuclear scientist, as founding director, with some technical guidance by JLab. Nuclear scientists continue to play instrumental roles in improving the precision of dose delivery and measurement and facilitating accurate treatment plans to minimize radiation damage to nearby biological functions.

Current technology development for proton therapy is aimed at reducing its cost while improving its precision by adapting advances made initially for discovery science. The capital investment (and footprint) needed to build a clinic will be reduced by a factor of five or so for upcoming installations by exploiting compact superconducting accelerators and gantries for beam delivery to patients, along with permanent magnet beam transport lines. The efficiency of treatments will be enhanced and short- and long-term toxic side effects reduced by more widespread application of the technique of pencil beam scanning (see Figure 2), pioneered at the Paul Scherrer Institut in Switzerland, where a narrow beam is rapidly scanned laterally and in energy to produce a radiation dose that conforms accurately to a tumor of arbitrary shape, even in close proximity to critical healthy organs.
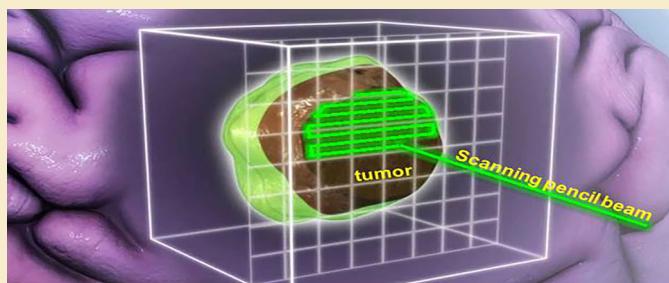
Figure 2: *An example of the technique of pencil beam scanning, used to deliver doses that conform accurately to a tumor of arbitrary but precise shape.*

Increased precision of irradiations relies not only on finer beam control but also on advanced dosimetry to

verify the dose profile in three dimensions on a phantom prior to delivery to a patient and to monitor the dose profile in two or more dimensions over a broad dynamic range in instantaneous dose rate during its delivery. Detection advances made for nuclear and particle physics are being adapted to these dosimetry goals by another John Cameron-founded company. For example, a recently developed water-based liquid scintillator can be exploited to make an active water phantom whose light yield profile, measured with CCD cameras, can verify each patient's individualized 3D treatment plan completely, rapidly, and with high spatial resolution. Noble gas scintillators or Gas Electron Multiplier (GEM) detectors can greatly improve the state of the dose monitoring art over existing ionization chamber arrays in resolution, response time, and linearity. *In-situ* dose verification with positron emission tomography (PET) using isotopes produced during the irradiation (^{11}C, ^{13}N, ^{15}O) is being exploited at TRIUMF in Vancouver, British Columbia.

Increasingly precise beam delivery will in parallel require increasingly accurate treatment planning simulation software (see Figure 3), based on more sophisticated dose calculation algorithms. Nuclear science is required here for input cross sections and to model particle

transport and also plays a role in developing advanced simulation techniques. To account for the higher cell killing power of protons as compared to X-rays, a relative biological effectiveness (RBE) value is applied to dose in proton therapy. Calculations based on particle energy deposition show that some ionizing tracks will deposit significantly more energy than others. These higher energy transfer tracks have a correspondingly higher RBE. Research merging nuclear science and biologic knowledge is underway in collaboration with scientists at JLab to improve treatment planning with better predictions for RBE, based on energy deposition and calculated using nuclear physics and simulation techniques in concert with radiation biology data.
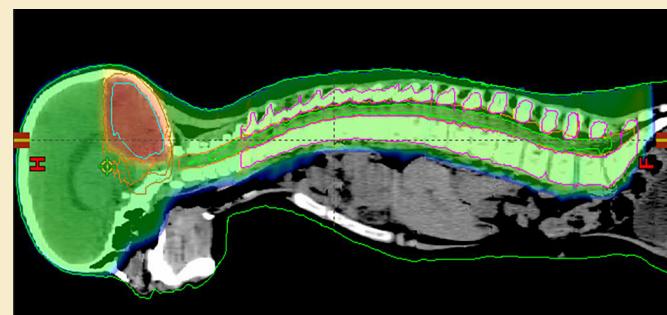
Figure 3: *An example of a pediatric medulloblastoma proton treatment plan depicting the characteristic precision matching of dose to tumor in the vicinity of the child's brain and spine.*

range to increase collision rates there by an order of magnitude, as needed to map the QCD phase diagram in a regime where current data hint at the existence of a first-order phase transition and a critical point between QGP and hadronic matter.

Heavy-Ion Detectors at RHIC
The RHIC detector suite comprises two large multi-subsystem detectors, PHENIX and STAR, which have played major roles in initially discovering the QGP and in characterizing its behavior and properties. Both detectors have seen a natural evolution over time, embedding specific equipment upgrades, most recently precision vertex detectors and improved heavy-flavor identification. Ancillary detectors along the RHIC beam line, such as zero-degree calorimeters and proton beam polarimeters, have proven instrumental to tag specific events to help understand the inner workings and flow within the thermal QCD matter and to facilitate the auxiliary program investigating the proton's spin structure.

To complete RHIC's scientific mission, both STAR and PHENIX detectors foresee further upgrades to take full advantage of the increased collision luminosity. These range from targeted upgrades of the STAR detector to a largely new sPHENIX detector. The STAR detector's central element was and remains a large cylindrical time projection chamber housed in a solenoidal magnet. STAR's envisioned upgrades focus on the second phase of a beam energy scan to map the phase boundary between QGP and hadron matter. This would include upgrades of the inner sectors of the STAR time-projection chamber to handle the higher luminosity while also improving resolution and extending acceptance, the addition of an event-plane detector, and a series of mid-rapidity and forward upgrades.

The PHENIX detector is currently optimized for the detection of leptons, photons, and hadrons (including those from jet fragmentation) in selected directions at high counting rates. PHENIX has submitted a proposal to the DOE for a Major Item of Equipment to construct

sPHENIX. sPHENIX would be built around the acquired BaBar solenoid magnet and would replace the central detectors of PHENIX with full hadronic and electro-magnetic calorimetry along with charged particle tracking. The new apparatus would dramatically extend the range of jets measurable at RHIC and provide the acceptance and resolution needed to study the sequential melting in QGP of different quark-antiquark bound states (e.g., different states of the upsilon). It would open a detailed investigation through jets and heavy quarks of the dynamics of QGP where its coupling is at the strongest. A smooth evolution to a detector for the EIC would be possible and is folded into the design.

The Electron Ion Collider (EIC)

Two independent designs for a future EIC have evolved in the United States. Both use the existing infrastructure and facilities available to the U.S. nuclear science community. At BNL the eRHIC design (Figure 7.1, top) utilizes a new facility based on an Energy Recovery Linac (ERL) to be built inside the RHIC tunnel to accelerate electron beams and collide them with RHIC's existing high-energy polarized proton and nuclear beams. At JLab, the Medium Energy Electron Ion Collider (MEIC) design (Figure 7.1, bottom) employs a new electron and ion collider ring complex together with the 12-GeV upgraded CEBAF, now under construction, to achieve similar collision parameters.

The EIC requirements in terms of beam polarization, beam species, range in center of mass energies, and high collision luminosity will push accelerator designs to the limits of current technology and will, therefore, need significant R&D. Cooling of the hadron beam is essential to attain the luminosities demanded by the science. The development of coherent electron cooling is now underway at BNL, while the JLab design is based on conventional electron cooling techniques but proposes to extend them to significantly higher energy and to use bunched electron beams for the first time.

An energy recovery linac at the highest possible energy and intensity is key to the realization of eRHIC at BNL, and this technology is also important for electron cooling in MEIC at JLab. The eRHIC design at BNL also requires a polarized electron source that would be an order of magnitude higher in intensity than the current state of the art, while the MEIC design at JLab would utilize a novel figure-eight storage ring design to maintain beam polarization for both electrons and ions.

The physics-driven requirements on the EIC accelerator parameters and extreme demands on the kinematic coverage for measurements make integration of the detector into the accelerator a particularly challenging feature of the design. Lessons learned from past experience at HERA at DESY in Germany have been considered while designing the EIC interaction region.
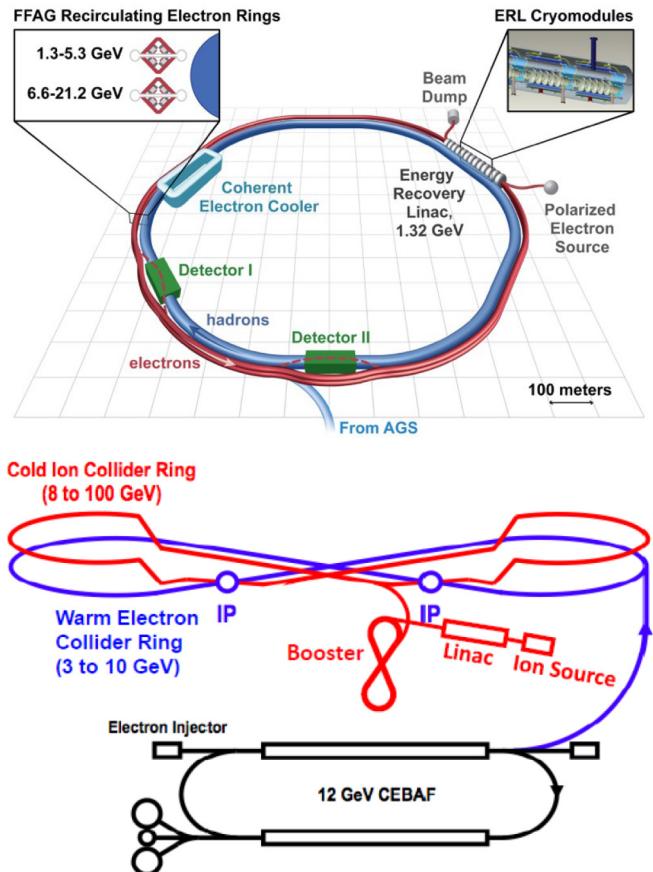
Figure 7.1: Top: The schematic of eRHIC at BNL, which would require construction of an electron beam facility (red) to collide with the RHIC blue beam at up to three interaction points. Bottom: The schematic layout of MEIC at JLab includes the 12-GEV CEBAF and would require construction of an ion linac, an ion collider ring (red), and an electron collider ring (blue) for collisions at two interaction points.

Driven by the demand for high precision on particle detection and identification of final state particles in both e+p and e+A programs, modern particle detector systems will be at the heart of the EIC. Generic research and design efforts are under way on various novel ideas for detectors, including compact calorimetry, various tracking and particle identification detectors, and high radiation tolerance for electronics. Meeting these challenges will keep the U.S. nuclear science community at the cutting edge in both accelerator and detector technology.

Facilities for Nuclear Structure and Nuclear Astrophysics

Nuclear structure research and nuclear astrophysics research require a diverse set of both rare and stable isotope facilities. The U.S. community operates two unique national user facilities as well as a spectrum of university laboratories, covering the required capabilities. One major new facility, FRIB, is under construction.

Existing Facilities

The Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL) is a DOE-funded national user facility for the investigation of nuclear structure and reactions near the Coulomb barrier, using a wide range of state-of-the-art instrumentation. The high-intensity stable beam program is complemented by rare isotope beams, with both in-flight production and fission fragment beams from the Californium Rare Ion Breeder Upgrade (CARIBU) using a ^{252}Cf fission source. CARIBU provides access to refractory elements not available at classical Isotope Separation On-Line (ISOL) facilities. Ongoing upgrades include an EBIS charge-breeder for CARIBU reaccelerated beams, the recoil separator AIRIS for in-flight radioactive beams, and the gas-filled spectrometer AGFA for rare reaction recoils.

The National Superconducting Cyclotron Laboratory (NSCL) at MSU is an NSF-funded national user facility focusing on the study of nuclear structure and astrophysics using rare isotopes. Rare isotope beams are produced by in-flight separation after fragmentation and fission of 50 to 200 MeV/nucleon heavy-ion beams from the coupled cyclotrons. Experimental programs are carried out with fast beams, stopped beams, and post-accelerated beams with 3–6 MeV/nucleon using the ReA3 heavy-ion linac. With the in-flight technique, all chemical elements can be reached, and most short-lived isotopes are accessible for reaction and decay experiments and studies of ground state properties.

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) supports ongoing research programs in nuclear structure, astrophysics, heavy element studies, fundamental interactions, symmetries, and technology R&D. It hosts the Berkeley Accelerator Space Effects facility, providing beams for radiation effects testing.

The U.S. university-based accelerator laboratories have formed the Association for Research at University Nuclear Accelerators (ARUNA), consisting of 12 institutions. ARUNA facilities provide a unique set of nuclear probes, often not available at national facilities. They offer flexibility and quick response to new research developments and challenges, and they play an important role in educating the next generation of highly qualified personnel.

For example, the NSF-funded John D. Fox Accelerator Laboratory at Florida State University is concentrating on light radioactive beams from the in-flight RESOLUT facility, using its 9-MV tandem accelerator and a superconducting LINAC booster. The Notre Dame Institute for Nuclear Structure and Astrophysics, also supported by the NSF, uses high intensity beams from three accelerators for, among others, a strong nuclear astrophysics program. The DOE-funded Texas A&M Cyclotron Laboratory specializes on experiments with radioactive beams up to 70 MeV/nucleon and is progressing towards the T-REX upgrade, coupling both of its cyclotrons to produce, stop, and reaccelerate exotic nuclei. The DOE-funded Triangle Universities Nuclear Laboratory (TUNL) operates the tandem laboratory, the Laboratory for Experimental Nuclear Astrophysics (LENA), and the High Intensity γ-ray Source (HIγS), which is the world's most intense Compton γ-ray source in terms of γ/s/keV.

Facility for Rare Isotope Beams (FRIB)

FRIB, under construction at MSU, will be the world's most powerful radioactive beam facility, making nearly 80% of the isotopes predicted to exist for elements below uranium. It will use a continuous-wave superconducting heavy-ion driver linac capable of producing 400 kW beams of all elements from uranium (with a maximum energy of 200 MeV/nucleon) to protons (with a maximum energy of 500 MeV). Key to reaching the high beam power are the high-intensity heavy-ion electron cyclotron resonance (ECR) source that was developed at LBNL and the simultaneous acceleration of multiple heavy-ion charge states in the superconducting linac. Charge stripping of this high intensity beam at an intermediate energy will be performed by a liquid lithium film, a technique developed at ANL. The high beam power level, and consequent intensity and reach, is unmatched at other existing facilities, or those now under construction or planned, around the world.

FRIB will provide intense beams of rare isotopes through in-flight fragmentation and fission of fast heavy-ion beams on thin targets. The rare isotopes will be

Sidebar 7.2: Nuclear Science Driving Accelerator Innovations

While generic accelerator R&D is the purview of the DOE Office of High Energy Physics, the demands of future nuclear science machines require project-specific R&D, which pushes the state of the art. Such demands have led, for example, to new developments in superconducting technology for radiofrequency (SRF) cavities and for magnets made from both conventional and newer high-temperature superconducting materials.

A major priority is to increase the level of polarization for as wide a range of ion beams as possible. This requires new sources, new ways to maintain the polarization during acceleration, and the development of accurate, fast, nonintrusive polarimeters. New high-intensity highly polarized sources are being developed for H⁻ and D⁻ ions and for fully ionized $^3He^{++}$ ions. The acceleration of polarized protons to high energy was spearheaded at RHIC, reaching over 60% beam polarization at 255 GeV. The EIC proposal at JLab (MEIC) contains a novel figure-eight accelerator to allow for high energy polarized deuteron beams. Accurate relative and absolute proton polarimeters have been developed at RHIC. Further R&D is needed to reach the 2% accuracy in absolute uncertainty for proton polarization and for effective polarimeters for high energy polarized deuteron and ^3He beams needed for a future EIC facility.
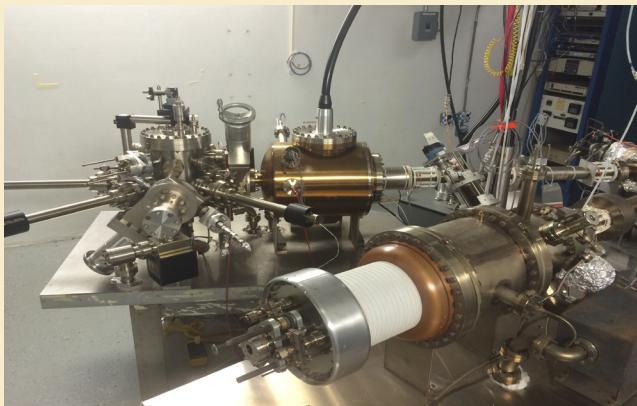
JLab pioneered high-intensity continuous electron sources (see Figure 1) with beam polarization up to 90%, essential for the CEBAF physics program. Even higher intensities of polarized electron beam are being pursued at BNL and MIT for their EIC proposal (eRHIC). Record unpolarized high-brightness electron beam sources have been demonstrated at Cornell, and R&D is underway at BNL and JLab for even higher intensities needed for electron cooling projects. Beam cooling can reduce the ion beam sizes and increase the luminosity of colliders (see Figure 2). A future high-luminosity EIC relies on a small ion beam size by electron cooling at energies above those achieved with continuous electron beams. BNL is studying bunched beam cooling for RHIC, with an energy recovery linac in the second phase, and is developing coherent electron cooling that promises very fast cooling times at high energies. JLab is studying an electron circulator-cooling ring that requires control of coherent synchrotron radiation.
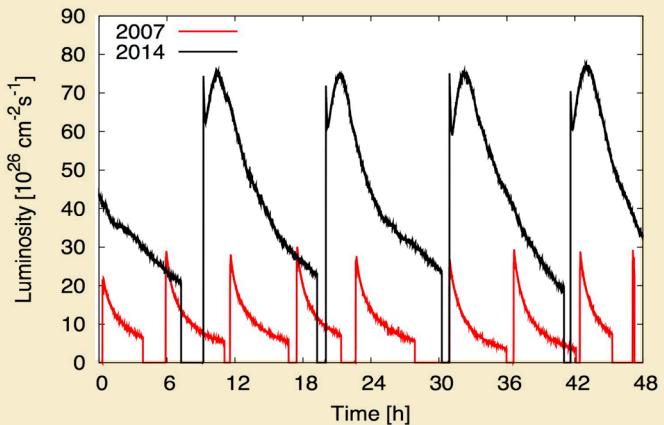
Figure 2: *A breakthrough in stochastic beam cooling was able to overcome the internal heating process of the high-energy heavy-ion beams of the Brookhaven RHIC and reduce the beam width up to fivefold. With the brighter beams, the collision frequency or luminosity was vastly increased.*

The construction of the FRIB at Michigan State University has led to the development of innovative designs of SRF cavities for efficient acceleration of heavy ions with low and intermediate velocities to half the speed of light. Extensive operating experience has been gained with such cavities at the ATLAS facility at ANL and at TRIUMF. These innovations and the gained operating experience will have an impact in many fields.

Figure 1: *Over 20 years of R&D have dramatically increased the performance of polarized electron sources. Foreground: early-generation source. Back: recent load-lock, ultra-high vacuum source using super-lattice GaAs/GaAsP photocathodes. Such sources can deliver a record 4 mA, 90% polarized electron current.*

collected and separated by a high-efficiency fragment separator for fast beam experiments. They will also be delivered to a gas cell for collection, combined with gas stopping and subsequent reacceleration using an EBIS for charge breeding before injection into the ReA heavy-ion linac. Harvesting of isotopes from the primary beam dump or after early stages of the fragment separator is also foreseen for use in experiments as well as societal applications like nuclear medicine and materials science. Beams not readily available at facilities using the complementary ISOL production method can be produced, and nearly any isotope can be made available with limited development time.

The full complement of fast, stopped, and reaccelerated beams will be available for experiments with a broad suite of equipment. FRIB is scheduled for a project completion in 2022 but aims for an early completion in 2020. There are a number of key upgrade possibilities after FRIB is completed. Space has been left in the linac tunnel to accommodate additional cryomodules, which would raise the production energy from 200 MeV/nucleon to 400 MeV/nucleon. This critical upgrade would increase the secondary beam yields by an order of magnitude. Other upgrade options are an ISOL production target, a second injector for simultaneous beam operation, and a doubling of the experimental floor space for future research equipment.

Detectors for Nuclear Structure and Nuclear Astrophysics
Detectors foreseen for the nuclear structure and nuclear astrophysics programs are a mix of generic equipment useable at several facilities and dedicated equipment for use at a single facility. The development of new reaccelerated beam capabilities from CARIBU at ATLAS, ReA3 at NSCL, and soon T-REX at Texas A&M, together with increased in-flight production at ATLAS (with AIRIS) and Florida State University (with RESOLUT), provide unique opportunities for forefront research with both existing and improved instrumentation. FRIB has to be equipped with state-of-the-art new equipment to take full advantage of its novel capabilities.

GRETA will play a central role by adding significant new capabilities to existing facilities, such as ATLAS, NSCL, and ARUNA facilities, and as a centerpiece at FRIB for the physics opportunities with both fast-fragmentation and reaccelerated beams. Many of the anticipated benchmark experiments of the foreseen science

programs rely on high-resolution, high-efficiency in-flight γ-ray detection. The technology and the scientific impact of a γ-ray tracking array has already been demonstrated by GRETINA, a 1π segmented Ge detector array employing the same signal decomposition tracking technology as foreseen in GRETA, and the community is eagerly anticipating a full 4π GRETA array.

Much existing equipment at the NSCL and ATLAS, such as detectors for gamma rays, neutron detectors, laser atom traps, and spectrometers and recoil separators, will continue to be used routinely for experiments with rare isotopes at FRIB and elsewhere. Gammasphere with its enhanced capabilities through fully digital electronics will also continue to play an important role at several U.S. facilities. At the same time, multiple additional capabilities for important programs that cannot be addressed with existing equipment or existing facilities are under study. These include the measurement of low-background very low-energy astrophysics reactions, for example with a proposed high-intensity underground accelerator filling gaps in our understanding of stellar evolution, or reaction with unstable nuclei at FRIB using the proposed Separator for Capture Reactions (SECAR), key to modeling novae, X-ray bursts, and neutron star phenomena. Another key addition to FRIB is the proposed High-Rigidity Spectrometer (HRS) which would enable in-flight reaction experiments with the most neutron-rich nuclei available from FRIB. These extreme nuclei provide the most sensitive tests of nuclear models.

Facilities for Fundamental Symmetries and Neutrino Physics

Low-energy precision experiments using neutrons, muons, and rare isotopes, as well as the investigations of neutrino properties such as its mass, can provide critical tests of the Standard Model complementary to the high-energy frontier explored at the LHC. Such experiments are pursued at a number of facilities outlined below.

SURF, in Lead, South Dakota, provides laboratory space deep underground, where sensitive physics experiments can be shielded from backgrounds generated by cosmic radiation. SURF is located at the former Homestake gold mine, where Ray Davis performed his Nobel-winning solar neutrino experiment. In 2006 the property was donated to South Dakota and converted to an underground laboratory. The first two major physics

experiments at SURF are at a depth of 4,850 feet. These are the Large Underground Xenon (LUX) dark matter experiment (supported by the DOE Office of High Energy Physics) and the Majorana Demonstrator experiment, described below. Other experiments planned at SURF include a large-scale liquid argon detector for the Long Baseline Neutrino Facility, an international HEP project, and a high-intensity, low-energy accelerator facility for nuclear astrophysics experiments. SURF also features a low-background radio-assay counting facility.

Observation of neutrinoless double beta ($0\nu\beta\beta$) decay would determine the Majorana or Dirac nature of the neutrino and have far-reaching implications regarding physics beyond the Standard Model. For decay mediated by the exchange of Majorana neutrinos with masses in the inverted-hierarchy region ($m_{\beta\beta}$ = 15–50 meV) lifetimes are expected to be of the order 10^{27}–10^{28} years, thus providing only about one decay per year per ton of source material. To reach this challenging sensitivity requires experiments with a ton-scale source mass and extreme control of backgrounds. We describe here the two current efforts being carried out at U.S. sites, with efforts at foreign sites but with substantial U.S. participation discussed later in this chapter in the International Collaborations and Facilities section.

The Majorana Demonstrator (MJD) experiment is a project funded by DOE-NP to prove the feasibility of a ton-scale next-generation search for $0\nu\beta\beta$ decay of ^{76}Ge. MJD is being constructed in an underground clean room at SURF and will comprise two cryostats, each of which houses 20 kg of high-purity ^{76}Ge as both source and detector. Most of the detectors are from 86%-enriched ^{76}Ge. Germanium semiconductor detectors have intrinsically low backgrounds and superb energy resolution. The challenge is to reduce the environmental backgrounds by about a factor of 100 below previous limits by the use of ultralow background materials for all cryostat components, a layered shield of electroformed copper, high-purity copper and lead, a radon-exclusion enclosure, an active muon veto, and a neutron moderator/absorber. Construction of MJD is scheduled for completion by September 2016.

The Enriched Xenon Observatory (EXO) experiment searches for $0\nu\beta\beta$ decay in another nucleus with different technology. It uses a time projection chamber filled with liquid xenon (LXe) enriched in the isotope

^{136}Xe. Advantages to using xenon for a $0\nu\beta\beta$ search include the relative ease to purify and enrich and that the ^{136}Xe decay energy allows discrimination against many sources of background. However, the energy resolution is poorer than that of germanium. The EXO experiment currently has two phases.

- A 200-kilogram prototype experiment, EXO-200, at the Waste Isolation Pilot Plant (WIPP) in New Mexico is funded by DOE-HEP. It has measured the two-neutrino mode of ^{136}Xe double beta decay and sets a stringent limit on the $0\nu\beta\beta$ decay rate.

- nEXO ("next EXO") is a proposed ton-scale experiment, for which R&D and engineering studies are being performed to design a much larger xenon detector and to find means to minimize backgrounds.

A next-generation direct neutrino mass measurement might be based on a radically new technique—cyclotron radiation emission spectroscopy (CRES)—that is developed by a U.S.-led collaboration. R&D efforts have demonstrated the measurement of the energy of a single electron by its relativistic cyclotron radiation. Continued success could lead to a large-scale installation in the coming LRP period with the aim of an order of magnitude improvement in neutrino mass sensitivity compared to KATRIN, an ongoing tritium beta decay experiment based on a large spectrometer installed in Karlsruhe, Germany.

The Fundamental Neutron Physics Beamline (FnPB) facility, located at the Spallation Neutron Source (SNS) at ORNL, was designed to study the detailed nature of the interactions of elementary particles to address important questions in nuclear and particle physics, astrophysics, and cosmology. Of particular interest is the study of fundamental symmetries such as parity and time-reversal invariance and the manner in which they are violated in elementary particle interactions. Experiments performed or proposed at the FnPB include NPDGamma (completed in 2014), n-^{3}He (taking data today), Nab (under construction), and nEDM. The first and second of these experiments measure parity non-conserving asymmetries using polarized cold neutrons to study the weak interaction between quarks in the strangeness-conserving sector in simple systems not complicated by nuclear structure effects. The third is an accurate determination of correlation coefficients describing neutron β-decay to test the completeness of the

three-family picture of the Standard Model. The fourth experiment, which lies at the heart of modern cosmology and particle physics, involves the search for the neutron electric dipole moment (nEDM). This experiment would improve sensitivity by two orders of magnitude over the best existing searches for CP violation beyond the Standard Model, as needed to account for the baryon asymmetry of the universe.

The ultracold neutron (UCN) facility at Los Alamos National Lab is the only currently operating UCN source in North America and provides UCN densities comparable to the world's other sources (located in Europe and Japan). Following the ongoing successful UCNA experiment on the neutron beta decay asymmetry, the facility will host the neutron lifetime measurement UCNτ, detector development for the Nab and UCNB experiments, the applied nuclear physics experiment UCNS, and neutron guide and storage cell development. A more precise determination of the neutron decay lifetime can be used to determine the CKM matrix element V_{ud} with high precision in a fashion that is relatively free of theoretical uncertainties. Complementary precision studies using decays of rare isotopes are being carried out at ANL using ion and atom traps.

The Fermilab Muon Campus is being developed to host two high-priority approved experiments that will challenge the Standard Model. While primary support comes from DOE-HEP, many nuclear physics groups and international partners are playing leading roles in these interdisciplinary experiments. The Muon g-2 Experiment will measure the anomalous magnetic moment of the muon to the unprecedented precision of 140 parts per billion. The result will either confirm or refute a long-standing discrepancy between the Standard Model and the previous measurement. The Mu2e Experiment will study the low-energy (essentially forbidden) process of coherent conversion of a muon to an electron from an atomically bound muonic atom. The goal is a four orders of magnitude improvement in the limit of this charged-lepton-violating process, with single event sensitivity approaching 1 part in 10^{17}.

ADVANCED TECHNOLOGIES

Advanced Computing

Computation now plays an essential role in every area of nuclear physics research (Sidebar 7.3). Nuclear physicists exploit available computational resources, ranging from leadership-class capability computing resources, such as Titan at OLCF and Mira at ALCF, through capacity (mid-scale) computing resources, such as Edison at the National Energy Research Scientific Computing Center (NERSC) and USQCD hardware at JLab, BNL, and Fermilab, as well as university clusters and small local clusters and workstations. The capability resources are allocated in programs such as INCITE and ALCC through peer-reviewed proposals in competition with other areas of science. Nuclear physics has obtained an approximately constant fraction (12%) of the national resources during the last several years. Access to capacity computing resources at NERSC and through the XSEDE program is also obtained through a proposal process. In addition, the USQCD project operates its own capacity computers, supported jointly by the DOE Offices of Nuclear Physics and High Energy Physics. In addition to the homogeneous machines it operates in the form of clusters and a Blue-Gene/Q, USQCD has invested in heterogeneous machines, primarily those accelerated with nVidia Graphics Processing Units (GPUs). GPU machines, through the development of very efficient software, have proven to be effective in many aspects of LQCD calculations.

Ten years ago, the capability, capacity, and local clusters were essentially of the same architecture, comprised of multiple homogeneous compute cores embedded in a fast communication fabric. Today, and into the future, the architectures are heterogeneous and diverse in nature. The limits of CMOS technology and the resulting failure to track Moore's Law, along with the power requirements of such technologies, make it necessary to embrace heterogeneous architectures. Two machine architectures are being pursued to deliver exascale computing resources within the next 10 years. One architecture is IBM Power-9 processors with Nvidia Volta GPUs being procured for Lawrence Livermore National Laboratory and Oak Ridge National Laboratory. The other is based on the evolution of Intel Xeon-Phi accelerators and will be deployed at Argonne National Laboratory as well as in the next NERSC machine.

Significant software development is required to exploit these two quite different architectures. Supported through the SciDAC program and in collaboration with the SciDAC Institutes, nuclear physicists collaborate to port and to optimize the performance of the code bases on these platforms. As an example, the Chroma

Sidebar 7.3: Towards the Future: Exascale Computing

Computational science continues to be a major capability on which nuclear physics relies. Computing in nuclear physics ranges from experimental data analysis and storage provided by the RHIC and ATLAS Computing Facility (see Figure 1) to the leadership-class computing facilities used by theorists for solving problems ranging from LQCD to stellar explosions. The field strongly benefits from the significant federal investment in computational hardware, applied mathematics R&D, and computer science.

Figure 1: The RHIC and ATLAS Computing Facility, Source: BNL.

High performance computing (HPC) at the exascale will enable the solution of vastly more accurate predictive models and the analysis of massive quantities of data. This propels scientific efforts across the globe, and near the end of this 2015 Long Range Plan, we will see exascale computational capability deployed in the U.S. and elsewhere. Today, the fastest computer in the world resides in China with a Linpack benchmark performance of 33.9 PFLOP/s or nearly 34,000,000,000,000,000 floating point operations per second (1 PFLOP = 10^{15} FLOP). The current fastest computer in the United States, Titan, resides at ORNL and boasts 17.6 PFLOP/s. Recently the Collaboration of Oak Ridge, Argonne, and Livermore (CORAL) was awarded a contract to build two 100–200 PFLOP/s computers by around 2017 (see Figure 2). The worldwide race is on to crack the exaflop (1000 PFLOP/s) computing ceiling within the decade.

Scientists utilize these incredible HPC resources to solve problems relevant to the DOE and Office of Science missions but also to the environment, national security, and the economy. Beyond nuclear physics,

exascale computing will push the frontier of modeling of climate, of new designs for renewable energy resources, of reverse engineering of the human brain, and of development of innovative products or medical techniques. The types of challenging computational problems to be addressed in nuclear physics, enabled by fruitful partnership of the Office of Advanced Scientific Computing Research and the Office of Nuclear Physics, include, for example, those of LQCD, first-principle understanding of nuclear reactions such as fission, design of advanced experimental facilities such as accelerators, and stockpile stewardship.

Figure 2: Oak Ridge National Laboratory will host one of the CORAL machines, called Summit.

Computational investments also directly impact our forefront experiments, considering the increases in data that will come from the LHC energy and luminosity upgrades in this decade leading to 100 times the data compared to today. The U.S. investment in computational capability is essential to handle this increased data flow. While computational capability in the U.S. is primarily focused on scientific computing, it is widely acknowledged that scientific data management must be addressed as our experimental capability continues to grow.

As the U.S. computational capability evolves, U.S. scientists must be ready to take advantage of it. If we are to be ready, resources must be devoted to developing computational tools that will solve our challenging problems and will scale to the largest computers. The need for an increased investment in computational sciences for nuclear physics is urgent and is upon us.

code, developed by nuclear physicists, is used in LQCD calculations on the Titan system. It makes extensive use of the Just-In-Time (JIT) compilation framework to dynamically produce and execute code on the GPUs. Lattice grid-based operations are executed on the GPUs, and data are transferred to the front-end as necessary (e.g., for communications). The code is tuned for optimal performance on the particular GPU system. The impressive gains in time-to-solution, which minimize computing times as enabled by these software efforts, are shown in Figure 7.2. While Intel Xeon-Phi accelerators are in less common usage by nuclear physicists at this time, similar code development has allowed the USQCD software effort to port and optimize its most important routine, quark-propagator generation. A comparison between the single-node performance on GPU systems and Xeon-Phi systems shows they differ by roughly a factor of two. Exploiting emerging architectures requires continued and enhanced support for the needed collaborative efforts among nuclear physicists, computer scientists, and applied mathematicians.

Electronics and Detector Developments

The cutting-edge research carried out and proposed by nuclear scientists often places extraordinary performance demands on detectors and electronics, and these lead to technological breakthroughs that also find important applications in other fields. We highlight several recent and ongoing examples here (see Sidebar 7.4).
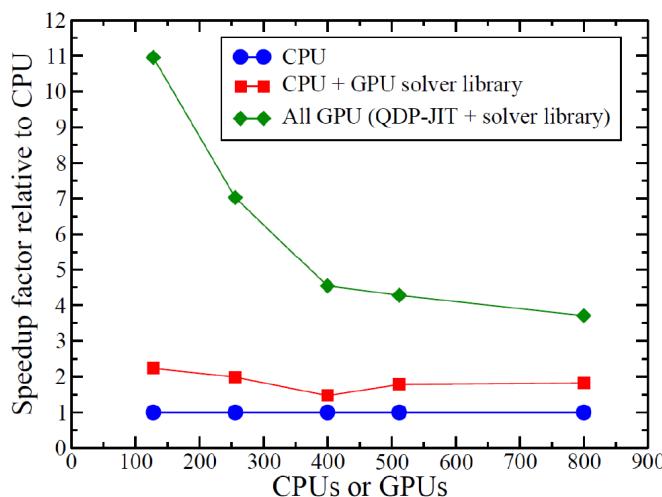
Figure 7.2: The strong reduction of time-to-solution as a result of software development is shown as the speedup gained as compared to the computing time with CPUs or GPUs only as the number of units increases. Shown are speedup factors only utilizing a solver library, and also including the QDP-JIT compilation framework on GPUs. [Image credit: B. Joo].

The need to resolve thousands of charged-particle tracks, emerging from a common vertex in relativistic heavy-ion collisions at RHIC and LHC, demands highly pixelized and compact vertex detectors. For example, the recently installed Heavy Flavor Tracker in the STAR detector at RHIC utilizes the new technology of Monolithic Active Pixel Sensors (MAPS), where the silicon sensor and readout electronics are combined with excellent signal-to-noise ratio and charge collection efficiency in each of millions of pixels. The barrel calorimeter readout within the high magnetic field environment of the new GlueX facility at JLab drove the need to use silicon photomultipliers—their first use in a large detector. The tracking of many gamma rays produced in a single nuclear reaction is even more challenging than charged-particle tracking but is demanded by advanced nuclear structure studies. The GRETA concept has been developed by nuclear scientists to use a large array of highly segmented germanium detector elements to determine the location and energy of every interaction of each gamma ray. The need for compact, cost-effective calorimetry in the proposed sPHENIX upgrade has stimulated R&D on dense tungsten powder detectors with embedded scintillating optical fibers to produce and transport light. The CUORE search for neutrinoless double beta decay utilizes a very different type of calorimetry, detecting the full energy of potential events via the tiny amount of heat the decay electrons produce in cryogenic bolometers. But the need to reduce backgrounds even further for next-generation searches is leading to the develop-ment of bolometers that simultaneously produce light output to facilitate improved particle discrimination. The neutron electric dipole moment search at SNS hopes to achieve unprecedented sensitivity, based on the novel injection of polarized ^{3}He to provide both precise monitoring of the magnetic field and a detection process sensitive to the spin precession rate of the trapped ultracold neutrons. Realization of this approach requires innovative cryogenic systems without metal surfaces on which the ^{3}He nuclei would depolarize.

There are also numerous broader applications of detector and electronics technology developed for basic nuclear physics research, of which we mention only a few recent examples. The miniaturization and increased channel density of application-specific integrated circuits, demanded by many experiments with high channel counts, has facilitated the development of miniature PET scanners that can fit around a wrist, a

plant root, or even the head of a conscious rat to allow simultaneous magnetic resonance imaging and PET imaging. Silicon photomultipliers offer advantages to medical imaging applications since they are low-voltage devices. The development of 3D position-sensitive solid-state detectors, combining small pixels with depth-sensing signal readout, has homeland security applications. The development of a novel water-based liquid scintillator material for very large detectors searching for very rare events is being adapted to provide an active water phantom to carry out 3D dose profile verification for precision patient-specific proton radiotherapy treatments.

Cryogenic and Polarized Targets

The requirements of precision science have driven the development of high-power cryogenic and novel dilution-free targets with high degrees of nuclear polarization, pushing towards the ultimate 100%. The Qweak experiment at JLab used the world's highest power cryogenic target (2.5 kW, 0.35 m liquid hydrogen). Building on the success of this target design, which was aided by computational fluid dynamics, a possible 5 kW target is being studied for a parity-violating Møller scattering experiment.

Recent advances in polarization technology have resulted in significantly improved performance of high-pressure polarized ^{3}He targets. For example, a Hall-A experiment at JLab ran with ~65% polarization and a luminosity of nearly 10^{37} cm^{-2}s^{-1}. Furthermore, spectrally narrowed high-power lasers in combination with convection-driven gas flow in polarized ^{3}He targets may enable factors of four to five higher luminosity. A polarized target using solid hydrogen-deuteride (HDice) provides pure samples of protons and deuterons with large polarization, polarized at high field (15T) and low temperature (0.010 K) and brought to a frozen-spin state. This target served as a polarized neutron target in recent photoproduction experiments in Hall B at JLab to complement measurements on polarized protons. Following this success, a transversely polarized HDIce target is under development that would withstand low-current electron beams without depolarization. Dynamically polarized targets such as NH_3 and ND_3 can withstand higher beam currents, albeit not dilution free. Such targets are under development to provide longitudinally and transversely polarized targets for several experiments at JLab. A tensor-polarized

deuteron target, with polarizations reaching above 30% and up to 40%, is under development to measure spin structure in a spin-1 nucleus in Hall C at JLab.

INTERNATIONAL COLLABORATIONS AND FACILITIES

Nuclear Science: A Worldwide Endeavor

Most advanced countries have recognized the long-term economic benefit of investments in basic research. In nuclear science, the U.S. is hardly alone in developing and planning forefront facilities and tools. Europe, Canada, and Japan have long been important players in nuclear research, and, more recently, China and South Korea have significantly enhanced their roles. The complementarity of facilities available in different countries, combined with the growing size of collaborations needed to carry out increasingly demanding experiments and computer-intensive calculations, offer enhanced opportunities for international cooperation in research and in the training of young scientists. Working Group 9 (WG9) of the International Union of Pure and Applied Physics was formed in 2003 to foster such cooperation in nuclear science. A comprehensive and regularly updated overview of capabilities around the world, published by WG9, is provided in Report 41 "Research Facilities in Nuclear Physics."[1]

Presently, anywhere from a third to a half of the users at flagship U.S. nuclear science facilities (RHIC, CEBAF, NSCL, ATLAS) are foreign. The foreign users are not only making crucial contributions to the intellectual goals, data analysis, and publications in U.S.-based experiments but also have contributed significantly to the funding and construction of forefront instrumentation and take on leadership roles in the collaborations. Meanwhile, participation of U.S. scientists in nuclear research abroad has grown significantly since the last Long Range Plan, taking advantage of capabilities not available in the U.S. Major contributions to that growth are associated with the launch of relativistic heavy-ion collisions at CERN's LHC and strong U.S. contingents in neutrino physics experiments mounted at underground laboratories in Canada (SNOLab), Italy (Gran Sasso), Japan (Kamioka), China (Daya Bay), and Spain (Canfranc). Other significant continuing U.S. contributions at

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1 http://www.triumf.info/hosted/iupap/icnp/report41.html

The 2015 Long Range Plan for Nuclear Science

accelerator facilities in Canada, Europe, and Japan are highlighted below.

Strong international cooperation also marks forefront efforts in nuclear theory. Many U.S. researchers have led scientific programs at the European Center for Theoretical Studies (ECT*) in Trento, Italy (at least one U.S.-based physicist is always a member of its Scientific Board), while many foreign scientists have led programs at the U.S. Institute for Nuclear Theory in Seattle. International collaborations have been critical to progress on large-scale computational projects in LQCD and supernova simulations. Targeted topical centers, such as the RIKEN BNL Research Center (RBRC) at Brookhaven and the Japan-U.S. Theory Institute for Physics with Exotic Nuclei (JUSTIPEN), have led to dramatic advances and also served to train some of the most promising young theorists in the field. More generally, postgraduate education in nuclear science for many foreign Ph.D. students and postdocs at U.S. universities and laboratories has contributed enormously to the international flavor of the research, enhancing efforts both within the U.S. and abroad.

International Participation at U.S. Facilities

Here we illustrate examples of significant participation from abroad in select U.S.-hosted programs.

In *relativistic heavy-ion physics*, international participation—from more than a dozen countries—has a longstanding tradition and is vital to the success of the RHIC experimental program. In both the PHENIX and STAR experiments, collaborations of over 500 scientists each, almost 50% of the physicists are from outside the U.S. Over 40% of the PHENIX detector funding came from abroad with ongoing support of recent silicon vertex detector, muon trigger, and forward photon calorimeter upgrades. There are significant efforts towards sPHENIX from partners in Japan, Israel, Korea, and Russia. The international partners in STAR from Asia and Europe contributed to both the initial detector as well as recent and upcoming upgrades, including the inner Time Projection Chamber, Muon Detector, Heavy-Flavor Tracker, Forward Meson Spectrometer, computing resources, and High-Level Trigger. The RIKEN Institute of Japan also has provided support in excess of $100M to accelerator and detector components for the RHIC spin program.

The RIKEN BNL Research Center at BNL is supporting young scientists in the study of strong interactions through joint tenure-track faculty positions with U.S. institutions, postdoctoral positions, and by hosting visiting scientists from Japan. In experiment, RBRC is a full collaboration member of PHENIX. In nuclear theory, there are strong efforts in LQCD, in spin physics and perturbative QCD, and in theories relevant to hadronic collisions. RBRC holds several workshops on these topics each year. More than 50 former RBRC fellows and postdocs are now tenured faculty in the U.S., Japan, and Europe.

In *hadronic physics*, about one-third of the nearly 1400 users at JLab are international. There have been major detector contributions from France for photon and neutron detection in deeply virtual Compton scattering experiments; from Italy for ring imaging Cherenkov particle identification detectors; and a tagging system from the UK and Chile and Canada to support exotic meson searches. Physicists from Japan provided high-resolution magnetic spectrometers to initiate a hypernuclear physics program. Physicists from China are driving a science program around the foreseen SoLID apparatus.

In l*ow-energy nuclear physics*, approximately one-third of the nearly 1000 users at the NSCL and the nearly 360 users at the Argonne ATLAS facility are from other countries. They are a vital part of the scientific activity at these facilities but also contribute to select instrumentation at ATLAS and NSCL. The international community will also be heavily involved in the FRIB science program, with 44% of the FRIB User Organization being international.

In *nuclear theory*, fostering international cooperation is a key mission of the Institute for Nuclear Theory (INT). International participation at INT includes representation on the National Advisory Committee, co-organization of scientific programs, and about 200 international visitors per year. The INT also hires many foreign postdocs and graduate students, and currently 13 former INT postdocs hold faculty positions in Europe and Asia. The INT is a biennial host of an international TALENT summer school which brings advanced on-line nuclear theory courses to universities around the world. The international Institutes for Physics with Exotic Nuclei (JUSTIPEN and JUSEIPEN, with Japan; FUSTIPEN, with France; CUSTIPEN, with China) have been established in order to facilitate

Sidebar 7.4: Advancing Instrumentation and Education

While a growing fraction of nuclear science research is carried out at large international laboratories, individual university research groups play critical roles in the success of that research. These roles include the development of state-of-the-art instrumentation demanded by increasingly sophisticated experiments. These developments are fueled by the creativity of university faculty, staff, postdocs, and students and provide on-campus visibility that helps to attract new students. They provide formative technical problem-solving opportunities to educate the next generation of a skilled and highly in-demand U.S. work force, while contributing to forefront basic research. We highlight a few examples here, drawn from the full breadth of the U.S. nuclear science portfolio.

One of the most ambitious and technically demanding experiments described in this document is the proposal to improve the sensitivity to a possible time-reversal-violating electric dipole moment of the neutron by two orders of magnitude. A few university groups have taken on major responsibility to develop the advanced cryogenic systems needed to meet this exacting goal. For example, a group at the California Institute of Technology is prototyping and perfecting the central magnet package, where the spin precession of neutrons trapped in superfluid liquid helium will be measured for electric fields aligned alternately along and opposite the magnetic field. To keep systematic errors to the desired level, the magnetic field cannot vary by more than three parts per million over each centimeter. Another group at the University of Illinois is developing the cryogenic system to generate and transport spin-polarized ^{3}He into the measurement cells, where they provide an *in situ* monitor of the magnetic field and a detection device that captures trapped neutrons with extreme sensitivity to their spin orientation. The technical demands on the ^{3}He cryogenic system are unique, because the nuclei would depolarize in contact with typically used metal surfaces.

University-based laboratories can provide the next generation of scientists a unique hands-on experience with accelerator-based experiments, often not easily accessible at the national facilities, while at the same time involving the faculty and scientists at these facilities as an intellectual resource for the national

nuclear science program. The university-based ARUNA laboratories—the Association for Research at University Nuclear Accelerators—pursue research programs in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications, building bridges to other research communities. Some are operated as DOE Centers of Excellence and some have their funds strongly leveraged by the hosting universities. They benefit from their locations on university campuses and can often be the testing ground for new ideas. For instance, ARUNA laboratories have developed techniques for generating and utilizing high-intensity low-energy beams, which will be an important asset towards the development of the next generation of underground accelerator laboratories. The LENA facility (see Figure 1) at the Triangle Universities National Lab, for example, is completing an upgrade that will increase the beam intensity into the tens of mA range. Unlike the national facilities, the university-based accelerators can provide ample beam times and time to study and reduce backgrounds.
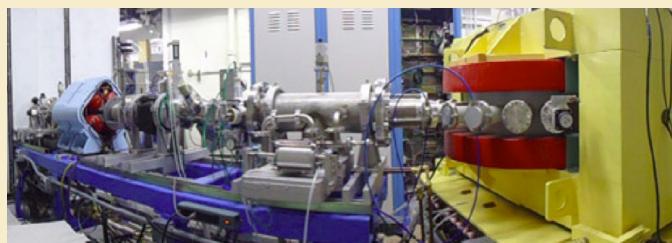
Figure 1: *University accelerator facilities such as LENA, the Laboratory for Experimental Nuclear Astrophysics at the Triangle Universities Nuclear Laboratory (TUNL), provide stable, neutron and gamma beams that are critical for measurements of astrophysical reactions that involve stable nuclei and govern the evolution of stars.*

Universities are also instrumental in developing detectors. As one major highlight, the detectors in the new Super-High Momentum Spectrometer in Hall C at Jefferson Lab are all user contributions. Whereas the spectrometer itself is part of the DOE 12-GeV Upgrade scope, all but two of the new detectors are built by universities, supported with two NSF major research instrumentation grants and a Canadian NSERC grant. One of the new detectors, an aerogel Cherenkov detector built at the Catholic University of America (see Figure 2), is based on aerogel with three different

indices of refraction for kaon identification in different momentum ranges, two of which reuse aerogel material earlier used in the MIT-BLAST detector, while the new third aerogel layer pushes this index to as low as possible to increase the kaon momentum range. One more detector found its way to the spectrometer through a collaborative effort of Armenia and the Netherlands. As a result of this combined effort, the spectrometer will provide for excellent tracking and particle identification capabilities.
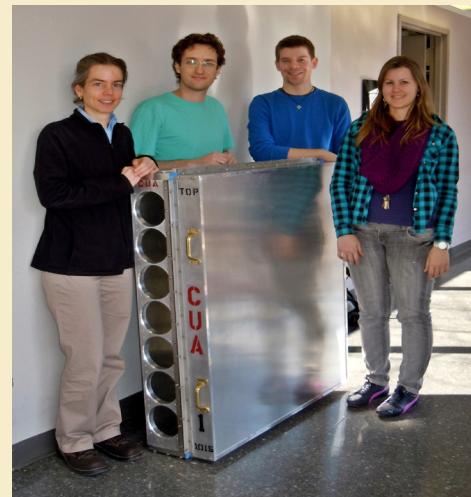
Figure 2: An aerogel Cherenkov detector, constructed at the Catholic University of America and ready for shipment to Jefferson Lab (photomultipliers are dismounted). The detector will be used for kaon identification in the new Super-High Momentum Spectrometer in Hall C. On the photo, from left to right: Prof. Tanja Horn, Ph.D. student Marco Carmignotto, undergraduate student Nathaniel Hlavin, and graduate student Julia Denes-Couto.

collaborations between U.S. and foreign scientists on low-energy nuclear physics. U.S. participation in these institutes is in the form of travel grants to support collaboration with foreign scientists.

U.S. Participation at Existing International Facilities and Emerging Opportunities

With large recent international investment in forefront nuclear science facilities worldwide, particularly in Europe and Asia, new frontiers in nuclear science research have rapidly opened. These represent greatly enhanced opportunities for the worldwide nuclear physics community. Around the world, countries are carefully seeking targeted areas to which they can contribute most significantly. This also means that for certain areas of nuclear science research the prime facilities are U.S.-based but that often unique and different opportunities also exist elsewhere. Here we will describe the greatly enhanced opportunities for the science described in this Long Range Plan as provided by the international facilities.

Hadron Physics

With the strong hadron physics activities at U.S. facilities, U.S. participation at international facilities is typically limited to a few groups spearheading select experimental efforts.

In *Europe*, a few U.S. groups participate in experiments at Mainz, Germany, the COMPASS-II experiment at CERN, or the planned PANDA experiment at GSI/FAIR, Germany, to carry out studies complementing programs at the U.S. facilities. Lastly, there is a strong involvement of U.S. scientists at the Paul Scherrer Institut (PSI) in Switzerland to extract the proton radius from low-energy elastic muon-proton scattering.

In *Asia*, the J-PARC facility in Japan can provide complementary pion and kaon beam experiments to provide required input to fully understand the spectrum of baryons. Heavy quark experiments at the BES-III facility in China address the nature of recently discovered narrow charmonium and bottomonium that are perhaps four-quark states. The planned 40-fold luminosity increase in the Super-KEKB electron-positron collider in Japan, coupled with improved particle identification and vertex detection capabilities in the BELLE-II detector, will supplement studies of the multi-dimensional hadron structure at JLab and BNL.

Heavy Ion Physics

LHC at CERN: The CERN LHC is the world's highest energy accelerator, at the energy frontier of both HEP—to study the recently discovered Higgs particle and search for physics beyond the Standard Model—as

well as NP to investigate QGP at the highest possible temperature. The LHC operates at much higher energy than RHIC and has unparalleled access to rare hard probes of QGP. The program is, however, less versatile in terms of beam energies and ion species than the dedicated RHIC facility.

Heavy-Ion detectors at the LHC - ALICE, CMS, ATLAS: The LHC at CERN has been in operation since 2010 for pp collisions with annual short Pb+Pb or p+Pb runs. Starting in 2015, the LHC will operate near design energy (5.1 TeV/nucleon pair Pb+Pb) with up to tenfold higher ion luminosity. U.S. scientists play leading roles at the LHC with about 160 U.S. nuclear physicists participating in the ion programs of the ALICE, ATLAS, and CMS collaborations.

The central part of the dedicated heavy-ion experiment ALICE contains a 7-m-diameter TPC as its primary tracking detector, a silicon micro-vertex tracker to identify decays of heavy quarks, a time-of-flight barrel and a high-momentum Cherenkov counter for particle identification, a transition radiation barrel for tagging high-momentum electrons, and a forward muon spectrometer. Within ALICE, the U.S. institutions lead the operations of the newly installed calorimeters (Figure 7.3) and steer the program of jet quenching measurements enabled by these detectors.

To cope with future interaction rates of up to 50 kHz, ALICE has started a major upgrade program for the central tracking detectors. The new silicon tracker and the new TPC readout chambers will be constructed and implemented with strong U.S. participation over the next three years.

The pp experiments CMS and ATLAS are state-of-the-art hermetic high-energy collider detectors with central micro-vertex trackers, large spectrometer magnets, calorimetry, and external muon trackers. Both have high rate capabilities required to handle the much-higher pp luminosity and feature unprecedented geometrical and kinematic coverage for charged particles, photons, electrons, muons, and jets.

ATLAS and CMS are preparing major upgrades to their capabilities that will greatly benefit the heavy-ion program. In CMS, the U.S. collaborators are actively participating in the level-one (L1) trigger upgrade; in ATLAS, they are planning on increasing their involvement in the L1 jet trigger upgrade.

Figure 7.3: *View of US-led ALICE ElectroMagnetic Calorimeter (EMCal) modules during installation in the ALICE experiment; one of the 10 EMCal modules, weighing over 7 tons, is being inserted.*

GSI/FAIR: The heavy-ion experiment CBM at the FAIR facility, currently under construction, will have the capability to extend the beam energy scan at RHIC towards lower energies to explore the QCD phase diagram in the region of compressed matter at very large baryon density.

Nuclear Structure and Astrophysics
The study of atomic nuclei with low-energy extracted rare isotopes began at CERN ISOLDE five decades ago. The ISOLDE facility remains world class for the production of rare isotopes produced via the isotope separation on-line (ISOL) production method and is completing its upgrade to HIE-ISOLDE with higher energy reaccelerated beams and higher primary beam intensities.

In *North America*, the ISAC facility at TRIUMF (Vancouver, Canada) is the highest power ISOL facility worldwide and the only ISOL facility in North America. ISAC complements the capabilities of stable beam and RIB facilities in the U.S. in unique ways, and there is a substantial U.S. user community pursuing these capabilities. TRIUMF is in the process of building the Advanced Rare Isotope Laboratory (ARIEL) that will add an electron linac driver for photofission and expand the existing proton beam production, enabling a full multiuser program.

In *Europe*, the SPIRAL facility at GANIL (France) provides additional ISOL capability, GANIL provides fast-beam capability, and the upgrade to SPIRAL2 will provide intense reaccelerated RIBs by the middle of the next decade. At the LNL-INFN (Italy) the SPES facility, currently under construction, will deliver accelerated fission fragment beams from an ISOL target. The NuSTAR program at FAIR (Germany), a major upgrade from the current in-flight program at GSI, will have RIBs with the highest energies (>1 GeV/nucleon) and will provide opportunities for unique experiments not possible at other facilities. U.S. scientists have expressed interest in exploring each of these unique opportunities.

In *Asia*, the Rare Isotope Beam Facility (RIBF) at RIKEN is currently a leading in-flight facility. U.S. scientists are participating in experiments in preparation for the forthcoming experimental program at FRIB, supported by a DOE program on Research Opportunities at Rare Isotope Beam Facilities. New facilities with in-flight RIB production capabilities are being developed in Korea (RAON) and China (HIAF), serving the regional needs of the low-energy community in Asia.

U.S. scientists are also involved in key experiments at facilities around the world for the production, study, and chemical properties of super heavy elements, enabled by rare trans-uranium targets from the U.S.

Fundamental Symmetries and Neutrinos
Neutrinos continue to fascinate, astound, and promise discoveries pointing to physics beyond the Standard Model. Even the mass of this lightest elementary particle is not determined, although numerous experiments provide upper or lower limits. Precision measurements of the neutron electric dipole moment, of neutron decay properties, and of electro-weak processes in rare isotopes can provide crucial tests of the Standard Model. U.S. researchers are involved in a number of efforts around the world, which are briefly described hereafter.

The KArlsruhe TRItium Neutrino (KATRIN) experiment in Karlsruhe, Germany, seeks to either measure the electron neutrino mass directly or to improve the laboratory limit by an order of magnitude to 0.2 eV. It will use ultra-high-precision measurements of electrons from tritium beta decay by means of a large (10-m diameter) spectrometer. KATRIN is currently in the commissioning phase. The KATRIN collaboration has more than 150 participants from 12 institutions, including five institutions from the U.S.

The Cryogenic Underground Observatory for Rare Events (CUORE), located at the Laboratori Nazionali del Gran Sasso in Italy, uses bolometers made from tellurium oxide crystals to search for neutrinoless double beta ($0\nu\beta\beta$) decay in ^{130}Te. The CUORE collaboration involves physicists from Italy and from four institutions from the U.S.

The KamLAND-Zen experiment in Japan reuses the 1-kton KamLAND liquid scintillator detector to perform a sensitive measurement of ^{136}Xe double beta decay. A first measurement using 300 kg of enriched Xe produced the best limits to date on the $0\nu\beta\beta$ decay of ^{136}Xe. A second improved phase with 600–800 kg isotope mass is being deployed. U.S. participation in KamLAND-Zen has carried over from the KamLAND effort, continuing support of the detector front-end and triggering electronics, the calibration system, and including data analysis and technical review.

The SNO+ experiment at SNOLAB in Sudbury, Canada, builds on the successful Sudbury Neutrino Observatory (SNO) program, in which U.S. scientists were involved. SNO+ will fill the existing SNO detector with liquid scintillator in place of the original heavy water for a broad program that includes solar neutrino observations, a search for $0\nu\beta\beta$ decay of ^{130}Te, as well as geoneutrino and reactor antineutrino measurements. SNO+ is located 6800 feet underground in the SNOLAB Laboratory in Sudbury, Ontario. The international SNO+ collaboration includes scientists from seven U.S. institutions.

The Paul Scherrer Institut (PSI) in Villigen, Switzerland, hosts a relatively low-energy proton accelerator, but with >1.3 MW, it is the highest beam-power accelerator in the world. It provides a new ultracold neutron source for a neutron EDM search. Secondary pion and muon beam lines are being utilized for the world's most sensitive ongoing test of charged lepton flavor violation, for muon capture on the deuteron and aluminum, as well as for muon-proton scattering at low energies. Many of these experiments involve U.S. university groups.

Several U.S. groups are involved in electro-weak precision experiments at the TRIUMF ISAC RIB facility, including the TRINAT magneto-optical trap and the DOE-NP-funded Francium Trapping Facility for the study of parity nonconserving atomic transitions in francium isotopes.

8. Workforce, Education, and Outreach in Nuclear Science

A highly qualified workforce trained in nuclear science is the most important element in realizing the scientific goals of the field. It is also vital to the Nation's health, economy, and security, as will be illustrated in Chapter 9, Broader Impacts. Norman Augustine, chair of the National Research Council (NRC) report, *Rising Above the Gathering Storm*, has said, "If America is to compete in our world, we've got to be competitive in critical fields, such as nuclear physics, if we are to have an economy, and without an economy, we are not going to solve the problems this Nation faces." The American Physical Society report, *Readiness of the U.S. Nuclear Workforce for the 21st Century Challenges* stated, "There will be a continuing, long-term, significant need for nuclear scientists and engineers in industry, government, and academia, across a wide range of applications."

Figure 8.1 shows the workforce of Ph.D.-level scientists and graduate students supported by NSF-NP and DOE-NP at universities and supported by DOE–NP at national laboratories from 2009 to 2013 as reported by the grantees to the agencies. The declining workforce since 2011 may be directly linked to the declining research budget profiles shown in Chapter 10. Figure 8.2 shows the number of Ph.D.s granted in nuclear physics each year from the NSF Survey of Earned Doctorates along with those in physics as a whole, elementary particle physics, and nuclear engineering. These numbers do not include the approximately 5–10 Ph.D.s per year in nuclear chemistry since this subfield is no longer listed as a separate subdiscipline in this survey. The trend in Ph.D. production has been approximately constant over the past decade, though at a level that is about 8% below that in the prior decade. 87 U.S. universities offer a Ph.D. in nuclear physics. Some of the largest departments, such as Massachusetts Institute of Technology or Michigan State University, may have several Ph.D. graduates per year while smaller groups may only average one every few years. Graduate training in nuclear chemistry is offered at only 25 of the 670 programs in chemistry. The relatively constant number of Ph.D.s indicates that the science continues to attract talented students from the U.S. and around the world. About 50% of the graduate students in physics are international.

As shown in Figure 8.3, about 40% of these Ph.D.s have careers outside of academia and basic research, providing critical leadership and innovation in medicine, national security, energy, and other industrial applications.

CHALLENGES IN U.S. EDUCATION AND THE TRAINING OF FUTURE SCIENCE LEADERS

The broad range of nuclear research, ranging from team sizes of single faculty members in nuclear theory at a university, to small groups performing most of their research at other university laboratories or national user facilities, to participation in large research teams at major research centers such as RHIC or CEBAF, provides an incredible array of opportunities for nuclear scientists early in their careers but brings with it significant challenges. In research at a local accelerator facility, a graduate student can participate hands-on in all aspects of an experiment, including design, building equipment, setup, data collection, and data analysis, and even have the experience of operating the accelerator itself. The small-group environments at these facilities provide opportunities for undergraduate and graduate students to work closely with postdocs and faculty, to have hands-on research experiences, and ultimately to provide leadership on their own projects. University groups with sufficient technical resources at their home institutions also contribute to activities associated with new initiatives, such as detector development, which again provide hands-on training to students in their graduate careers. In addition, the intellectual atmosphere of a university provides exposure to the full range of activities in physics and chemistry, as well as applied areas of research. The Association for Research at University Nuclear Accelerators (ARUNA) was founded in 2011 to strengthen the research and educational opportunities at these laboratories through enhanced communication and exchanges. Research at these 12 institutions spans the low-energy nuclear science research frontiers including studies in nuclear astrophysics, fundamental symmetries, and applications.
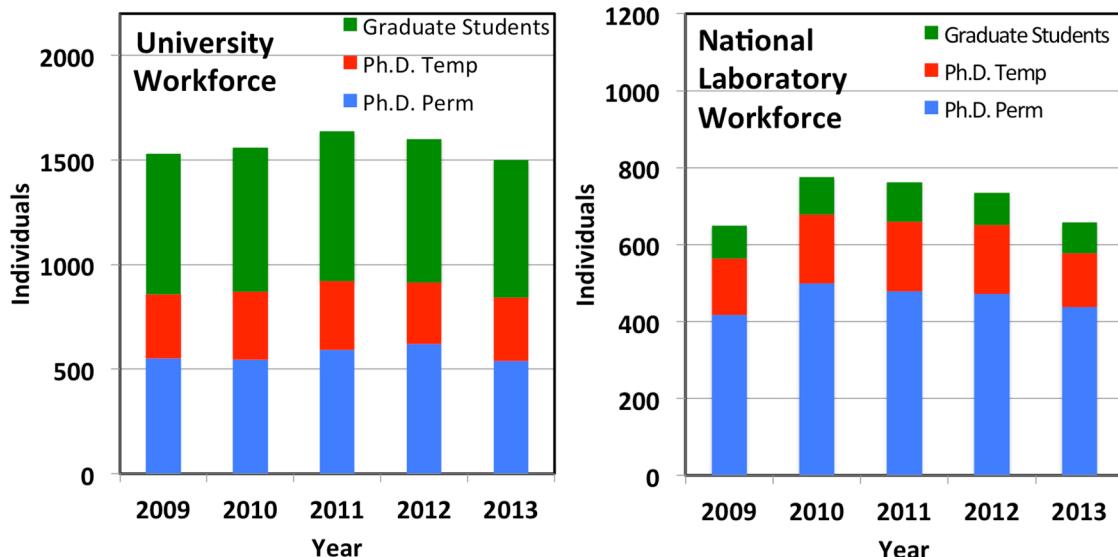
Figure 8.1: *Nuclear science permanent and temporary Ph.D. positions and graduate students funded by the DOE-NP and NSF-NP at universities (left panel) and funded by DOE-NP at national laboratories (right panel). The DOE data are taken from the NP FY 2013 Nuclear Physics Workforce Survey. The NSF data are the as-budgeted workforce statistics.*

Increasingly, experimental nuclear scientists are conducting their research at large centralized facilities. As a result, the role of university groups and the nature of graduate education in experimental nuclear science have evolved. Many graduate students begin their careers at a university taking courses, then gradually shift their activities to experimental research at one of the large facilities. This shift places new emphasis on the complementary role that national laboratories play in graduate education and the importance and challenges of opportunities for graduate students to be involved in all aspects of experimental research through working in partnership with mentors and advisors at the laboratories. While participating in teams of several hundred scientists, they can develop different skills, including those necessary for working in a large organization, that can be highly valuable to industry. These skills can include software management in large software projects, data analysis of large datasets, or being part of a team that is advancing the state of the art in an entirely new detection system.

At the other extreme, university-based nuclear theory groups are often small, which can limit the exposure of theory students to only a part of the full spectrum of ideas and styles in doing nuclear physics. As described later in this chapter, each of these environments has required new approaches to education for theoretical and experimental nuclear scientists to prepare them for research and applications.

Another challenge appears in the demographics of young faculty at our universities and as leaders in the scientific and technical enterprise in nuclear science. The U.S. continues to attract outstanding nuclear scientists. An increasing fraction of these individuals received their Ph.D.s outside of the United States. Figure 8.4 summarizes the percentage of current faculty who earned their Ph.D. from U.S. institutions compared to an assessment 10 years ago. The most outstanding early career nuclear scientists receive prestigious awards from the National Science Foundation (CAREER awards) and the Department of Energy (Early Career Awards). The country of Ph.D. of these awardees is summarized in Figure 8.5 and demonstrates that an increasing fraction of these most promising future leaders in nuclear science receive their Ph.D. education outside of the U.S. Even if an individual received the Ph.D. from a U.S. institution, many are foreign nationals, since, on average, about 50% of Ph.D. students in physics are international.

A key issue is whether the workforce trained in nuclear science is meeting the needs of the Nation. The 2004 NSAC report, *Education in Nuclear Science*, recommended "the nuclear science community work to increase the number of new Ph.D.'s in nuclear science by approximately 20% over the next five to ten years." This recommendation was based on a detailed survey that showed a predicted large number of retirements and an anticipated increase in homeland security areas.

However, the recommended increase in the annual number of Ph.D. degrees in nuclear science has not been realized. Rather, the number of new Ph.D.s per year has been at best flat (Figure 8.2) and is a smaller fraction of the total number of Ph.D.s in physics. As the nuclear science community upgrades its world-leading accelerator facilities CEBAF and RHIC, commissions FRIB, which is currently under construction, and plans for a next-generation EIC, it is critical that a highly talented, diverse workforce is available to realize the frontier scientific goals of these facilities and address the technological challenges required to enhance both the science and technology.
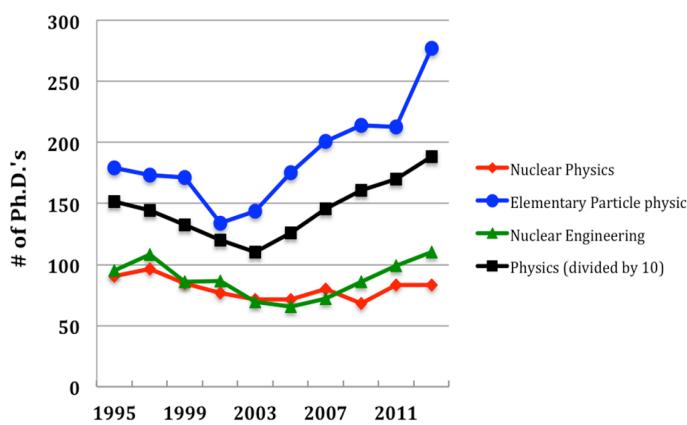
Figure 8.2: *Two-year averages of the number of Ph.D. degrees awarded from 1993 to 2013 in physics, elementary particle physics, nuclear engineering, and nuclear physics based on data from the NSF Survey of Earned Doctorates.*

The 2014 NSAC report, *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, summarized the challenges in recruiting and retaining a talented workforce at the DOE laboratories, in particular in nuclear science, radiochemistry, and accelerator and high-performance computing technologies. The laboratories have a need for U.S. citizens with strong backgrounds in these areas to not only support applications of these sciences but also with the foundation to build on this training for activities beyond what would be included in an academic curriculum, such as applications of nuclear science to nuclear security or forensics.

Nuclear chemistry continues to be an important subfield of nuclear science, not only for the scientific frontier it explores (such as chemistry of the heaviest elements) but also because of its impact on national needs, such as nuclear medicine, radiopharmaceutical chemistry, and nuclear waste disposal. The recruiting, education,

and training of Ph.D.s in nuclear and radiochemistry are even more at risk than in nuclear physics. A decade ago the NSF Survey of Earned Doctorates stopped including nuclear chemistry because so few (less than five) students reported receiving a Ph.D. in this subfield. The current training in nuclear chemistry is highly distributed, with faculty mentors in many different departments (chemistry, biology, engineering, medical schools) and with fragmented funding.
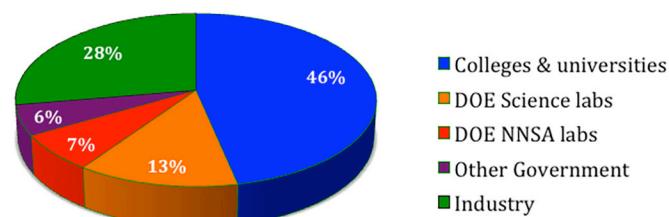
Figure 8.3: *Distribution of careers of nuclear science Ph.D. recipients from 2006 to 2009. Adopted from the 2015 white paper Nuclear Science Education and Innovation.*

The nuclear community has responded to address these challenges. New directions are being developed in graduate and postdoctoral education. There is a focus on undergraduate students as the key to increasing the pathways into the field. More broadly, outreach activities are essential to raise the recognition of the value of basic and applied nuclear research.
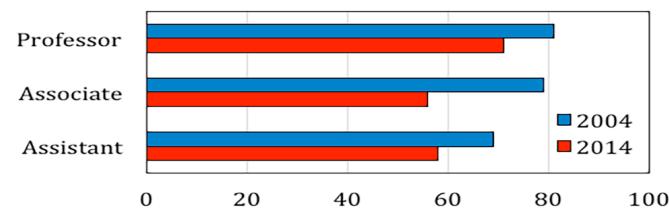
Figure 8.4: *Percentage of nuclear physics faculty at U.S. research institutions who earned their Ph.D. in the U.S. in 2004 compared to 2014. Adopted from the 2015 white paper Nuclear Science Education and Innovation.*

NEW DIRECTIONS IN GRADUATE AND POSTDOCTORAL EDUCATION AND TRAINING

Graduate education is at the heart of educational activities in nuclear science. Just as there have been accomplishments in advancing our understanding of the nucleus and nucleons, there have been new directions in the education and training of graduate students and postdoctoral scholars.

The field addressed the diverse backgrounds and possible isolation of students in smaller groups with a set of targeted development activities. The National Nuclear Physics Summer School (NNPSS) has been developed to complement the opportunities available at a single institution and to facilitate interactions among experimental and theoretical students in all subfields of nuclear science. In these summer schools, students meet not only other graduate students—their future colleagues—but also the leaders of the field, who offer lectures and lead discussions. To complement the more general overview of nuclear physics offered at NNPSS, many subfields of nuclear science host more specialized schools, such as Hampton University Graduate Studies (HUGS) in medium energy nuclear physics and the Exotic Beam Summer School, for students and postdocs interested in experimental and theoretical opportunities with rare isotope beams.
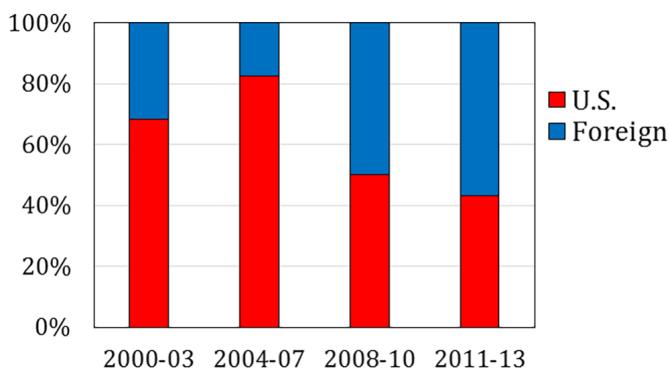
Figure 8.5: *Percentage of nuclear science early career award recipients who earned their Ph.D. degree in the U.S. Adopted from 2014 NSAC report Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Discipline, supplemented by information from the NSF.*

The new theoretical topical collaborations have developed innovative approaches to nuclear science education. The low-energy nuclear physics community has formed the TALENT (Training in Advanced Low Energy Nuclear Theory) educational initiative to provide advanced and comprehensive training to graduate students and early career researchers. The goals are to (i) develop a broad curriculum for cutting-edge theory to understand nuclei and nuclear reactions and astrophysics and (ii) build strong connections between universities and research laboratories and institutes worldwide to realize this curriculum. Future plans include developing a repository of consistent and well-linked teaching materials that exploit advances in active learning pedagogy and technological tools. In the relativistic heavy-ion community, summer schools have

been held adjacent to meetings of the JET topical theory collaboration. New topical collaborations are being assembled, each containing significant educational components.

Multidisciplinary research opportunities host innovative approaches to graduate and postdoctoral education and training. High-performance computing SciDAC initiatives require a collaboration of nuclear and computer scientists to help us understand the most complex problems in nuclear physics. Activities include the education of students and postdocs in high-performance computing algorithms and architectures. The Physics Frontier Centers are an NSF-initiative to foster research and education across boundaries. The Joint Institute for Nuclear Astrophysics (JINA) regularly hosts educational programs for students and postdocs, often exploiting distance learning.

The relatively small fraction of graduate students pursuing a degree in nuclear physics makes it difficult for departments to offer advanced specialized courses in a timely fashion. At the Massachusetts Institute of Technology, the desire to help a wide variety of students and departments is being solved by using a MOOC (Massive Online Open Courses) style approach. While MOOCs were developed to bring lectures to a large, global audience, they can also be used to teach a small number of students again and again. As a first attempt, a course on Effective Field Theory is being offered for free, worldwide and online.

A number of programs help address workforce shortages at the DOE laboratories. The DOE Office of Workforce Development for Teachers and Students initiated the Science Graduate Student Research Program (SCGSR) to provide opportunities for Ph.D. candidates to spend several months in residence at a DOE laboratory. The Fall 2014 inaugural group of 68 included 12 nuclear science students in experimental and theoretical, fundamental and applied research who were placed at seven different DOE laboratories. Their institutions and funding programs are summarized in Table 1.

Appreciating the needs for nuclear scientists, the National Nuclear Security Administration (NNSA) has made substantial investments to strengthen the education and training of nuclear scientists at U.S. universities. For over 10 years the Stewardship Science Academic Alliance (SSAA) program has supported

Table 1. DOE Science Graduate Research Program Awards Fall 2014

Awardee's Current Graduate Institution	Host DOE Laboratory	2014 SCGSR Priority Research Area
University of Iowa	ANL	Heavy Element Radiochemistry
University of Michigan-Ann Arbor	ANL	Heavy Element Radiochemistry
University of Missouri-Columbia	BNL	Isotope Development and Production for Research and Applications
Washington State University	INL	Heavy Element Radiochemistry
University of Vermont	LANL	Heavy Element Radiochemistry
Georgia State University	LANL	Heavy-Ion Nuclear Physics
Washington University in St. Louis	LANL	Low-Energy Nuclear Physics
Kent State University	LBNL	Heavy-Ion Nuclear Physics
University of Notre Dame	LBNL	Nuclear Theory
University of Georgia	SRNL	Applications of Nuclear Science & Technology
University of Tennessee, Knoxville	TJNAF	Medium Energy Nuclear Physics
Northwestern University	TJNAF	Medium Energy Nuclear Physics

Argonne National Laboratory (ANL)
Brookhaven National Laboratory (BNL)
Idaho National Laboratory (INL)
Lawrence Berkeley National Laboratory (LBNL)

Los Alamos National Laboratory (LANL)
Savannah River National Laboratory (SRNL)
Thomas Jefferson National Accelerator Facility (TJNAF)

university-based nuclear science research and technical development activities in low-energy nuclear science and, more recently, in radiochemistry. In 2015, 12 single-investigator awards and two centers are funded. An extremely important development is that the techniques required for forefront research with radioactive beams discussed in Chapter 3 match, in many cases, the issues important for stewardship science. The SSAA Center for Radioactive Ion Beam Studies for Stewardship Science was founded in 2003 and is a consortium of nine university and national laboratory groups in experimental and theoretical nuclear science that works in partnership with Los Alamos and Livermore National Laboratories. In 2011, the Nuclear Science and Security Consortium (NSSC) was founded at the University of California-Berkeley with support from the non-proliferation area of NNSA. The NSSC is a consortium of seven universities and four DOE laboratories, with significant collaborations with four-year college and minority-serving institutions across the U.S. The relationship between the disciplines and the national laboratories for these NNSA-supported efforts is displayed schematically in Figure 8.6.

The most talented undergraduate students are attracted to the prestigious fellowship opportunities offered by

the NSF, as well as the DOE Computational Science Graduate Fellowship (CSGF) and the Stewardship Science Graduate Fellowship (SSGF). In contrast, there is no analogous prestigious postdoctoral fellowship program in nuclear science to which graduate students could aspire and that would recognize exceptional postdoctoral scholars in nuclear science. Such a program is clearly needed.

These innovations in graduate education build on the tradition of broad education and training of nuclear scientists, preparing them for the full spectrum of careers meeting the Nation's needs.

UNDERGRADUATE EDUCATION AND RESEARCH—THE GATEWAY TO ADVANCED STUDIES AND RESEARCH

Central to addressing the challenges in attracting, educating, and training excellent U.S. students and preparing them for successful careers is undergraduate education and the need to engage undergraduate students early on in exciting research.

The nuclear physics community has recognized the importance of an early research experience for a long
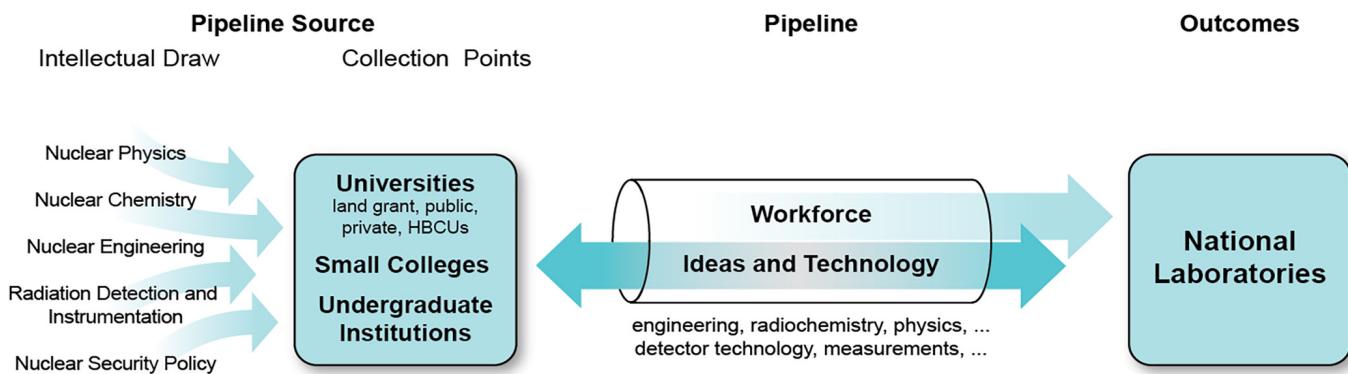
Figure 8.6: *Relationship between the universities and colleges and the DOE laboratories in activities supported by NNSA.*

time. Already in 1983 the NSAC Long Range Plan stated as the first recommendation with regards to workforce and training: "Programs which involve undergraduates in nuclear science research are extremely important in attracting students to the field … efforts should be made to strengthen and expand these … if necessary with specific funding from the agencies." When the NSF (re) instituted the Research Experiences for Undergraduates (REU) programs in 1987, half of the first successful proposals were led by nuclear physicists. The nuclear science community continues to take advantage of the REU and the DOE-sponsored Science Undergraduate Laboratory Internships (SULI) program. For example, out of the 48 physics REU sites in 2014 that specified a subfield of research, 40% of the programs listed nuclear physics as an option. Many of the members of the ARUNA consortium participate actively in REU programs, providing research opportunities for undergraduate students from colleges across the U.S., as well as at their home institution. P.J. LeBlanc, profiled in Sidebar 8.1, is an example of how his REU experience at the University of Notre Dame, an ARUNA founding member, set him on the path to success in industrial applications of his nuclear physics training. ARUNA laboratories also provide research opportunities for local students during the academic year with a significant number of these students conducting senior projects.

The crucial and important impact that a research experience has at the undergraduate level in nuclear physics is evidenced by the MoNA (Modular Neutron Array) collaboration of nine undergraduate institu-tions, one historically black college (HBCU), and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The MoNA collaboration is focused on studying the properties of neutron-rich unstable nuclei. Over the last 12 years,

more than 150 undergraduate students worked on MoNA research projects, from assembling and testing detectors to participating in experiments and analyzing data. Because of the composition of the collaboration, almost 80% of the students come from small liberal arts colleges, where they often do not have the opportunity to gain significant research experience. The impact of the MoNA collaboration has been broad, with former undergraduate participants now in faculty positions mentoring undergraduates in research and on the path to leadership in the next generation of nuclear scientists. Professor Mustafa Rajabali, profiled in Sidebar 8.1, is an example of a former MoNA undergraduate now introducing his own undergraduate students to the excitement of nuclear science research.

An especially effective recruiting program that is unique to nuclear physics is the Conference Experience for Undergraduate (CEU) program hosted annually at the Division of Nuclear Physics meeting. First organized in 1998 under the leadership of Professor Warren Rogers of Westmont College, this capstone for undergraduate research experiences has been very successful, with more than 1600 undergraduate participants in its first 16 years. As documented in Figure 8.7, a large fraction (about 85%) of CEU participants would consider nuclear science in their graduate study plans. The impact of the CEU opportunity has been strong, with many former participants now in faculty positions mentoring undergraduates in research on the path to becoming the next generation of nuclear science leaders. Former CEU participant Professor Anne Sickles is profiled in Sidebar 8.1.

In addition to the CEU opportunity, the DNP education committee annually compiles a comprehensive brochure of physics departments offering graduate research

programs in nuclear physics. In 2014 the brochure listed 52 programs. The brochure is available on the DNP website and is distributed to the CEU students, who value it as an important resource.
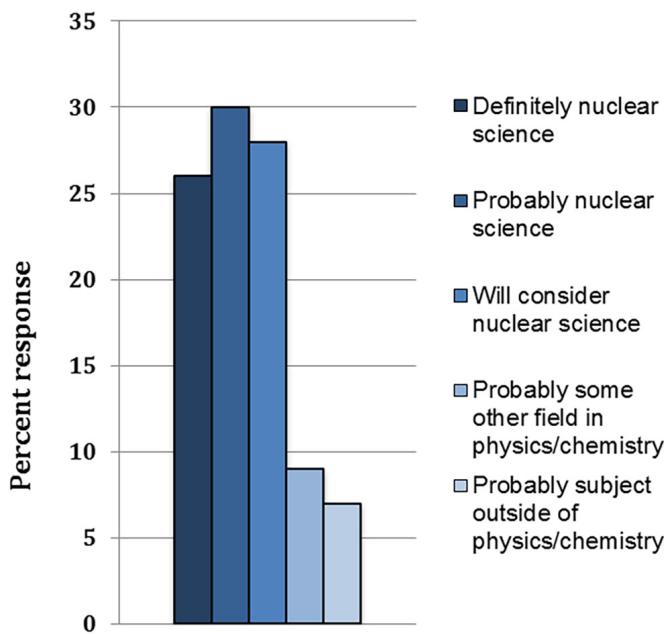
Figure 8.7: *Percentage of CEU participants who would consider nuclear science in their future graduate studies. Adopted from survey by Warren Rogers.*

A reduction of nuclear physics classroom and laboratory courses offered at the undergraduate level is one reason why a smaller fraction of graduate students select nuclear physics; they are not aware of the frontier research opportunities. The nuclear science community has begun to address this challenge by adopting several different approaches. The University of Rochester developed a laboratory course for nuclear science and technology for nuclear physics, chemistry, and engineering students. A nuclear physics summer school for basic nuclear physics has been funded through an NSF CAREER grant at Michigan State University, and efforts are under way to develop modules online that can be shared among institutions. The Nuclear Regulatory Commission (NRC) has also recognized the need to enhance education in nuclear science and is providing seed funding at the University of Notre Dame to start a new program in applications of nuclear physics, including nuclear energy, national security, and high-energy density physics.

For decades the Summer Schools in Nuclear and Radio Chemistry (SSNR) have been successful in attracting

undergraduate students to nuclear and radiochemistry and providing them with initial training. These schools, traditionally hosted in partnership with a DOE laboratory, are neither a research experience nor a course. Rather, they are training programs that provide extensive hands-on activities in this discipline that is under-served at universities. Nuclear and radiochemistry are of critical importance to the DOE laboratories in realizing their research, technology, and safety missions and providing the nation with the talented workforce for innovations in nuclear medicine in diagnosing and treating disease and applications in industry, energy, and national security. There are generally almost 200 applicants each year vying for a total of 24 slots at two locations. All participants must be U.S. citizens. About 50% of the recent Ph.D.s in nuclear and radiochemistry were initially trained at one of the SSNRs; this is a very large fraction of the U.S. citizen Ph.D.s in this field. Jo Ressler, an individual who benefited from the SSNR, is profiled in Sidebar 8.1. The two current sites of the SSNR are San Jose State University (original site) and Brookhaven National Laboratory (BNL). Previous NSAC and National Academy of Sciences reports have called for a third nuclear chemistry school to help serve the need for talented U.S. individuals in nuclear and radiochemistry, but to date this has not transpired. This training activity is critical to the missions of DOE and the national need for applications in national security, energy, and medicine.

Many other governmental agencies sponsor new directions in nuclear science education and training. The DOE Office of Nuclear Energy sponsors a Radiochemistry Fuel Cycle Summer School hosted by the University of Nevada-Las Vegas for up to 12 students each summer. In addition to an introduction to nuclear physics and radiochemistry, the students tour national facilities at General Atomics and the Nevada National Security Site. The Department of Homeland Security, Domestic Nuclear Detection Office, supports a National Nuclear Forensics Summer School, which is organized by Los Alamos National Laboratory and rotates between the University of Nevada-Las Vegas, Washington State University, and the University of Missouri. Up to 10 students participate each year in learning about nuclear physics and contemporary issues in nuclear forensics with a tour of a national laboratory, such as Pacific Northwest National Laboratory.
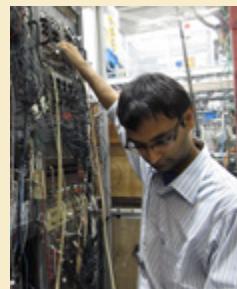
An increasingly larger fraction of U.S. college students comes from economically disadvantaged or other

Sidebar 8.1: Undergraduate Research Experiences: Pathway to Success in Fundamental and Applied Nuclear Science

Jo Ressler
Lawrence Livermore
*National Laboratory*

Jo Ressler is an exemplar of how the training from the Summer Schools in Nuclear and Radiochemistry (SSNR) set her on the path to making important contributions to the nuclear security of the U.S. Jo was in the 1995 class of SSNR at San Jose State University, which led to her Ph.D. studies in nuclear chemistry at the University of Maryland. Her dissertation work was based on research at Oak Ridge National Laboratory while she was in residence at Argonne National Laboratory. Upon receiving her Ph.D., she did postdoctoral work at Yale University followed by a faculty position at Simon Fraser University in Canada. In 2006 she joined the staff at Pacific Northwest National Laboratory and then Lawrence Livermore National Laboratory, where she has been a staff member since 2009. After leadership roles in nuclear nonproliferation, counterterrorism, and nuclear forensics applications of nuclear radiation detection and analysis techniques, she now works in nuclear security applications.

Mustafa Rajabali
Tennessee Technological
University

Mustafa Rajabali was one of the first undergraduate students in the MoNA collaboration. In 2002, as a student at Concordia College in Moorhead, Minnesota, he participated in the construction of the first layer of 16 scintillation detectors of the Modular Neutron Array, which had been funded by an NSF MRI grant. He participated in the first experiment at the NSCL with a subset of the detector and presented his research at the fifth CEU program at the 2002 DNP meeting in East Lansing, Michigan. After receiving his bachelor's degree in physics, mathematics, and chemistry, he entered the Master's program at North Dakota State University where he received his M.S. in condensed matter physics. He then returned to nuclear physics and received his Ph.D. from the University of Tennessee in 2009, working on β-decay, β-delayed neutron emission and isomer studies around ^{78}Ni. After completing two postdoc positions, at the University of Leuven in Belgium and TRIUMF in Canada, he joined the faculty at Tennessee Technological University, where he mentors undergraduate students in research in experimental nuclear physics and the application of radiation detection methods for research in geography, biology, and environmental science.

Anne Sickles
University of Illinois,
Urbana-Champaign

Anne Sickles participated in the second and third Conference Experience for Undergraduates (CEU) programs at the DNP meetings in Asilomar, California, and Williamsburg, Virginia, in 1999 and 2000, respectively. At the time she was an undergraduate student at Gonzaga University, and she presented posters on her summer research at Michigan State University and the University of Michigan. After receiving her bachelor's degree in physics, she went to graduate school at Stony Brook University where she received her Ph.D. in physics as part of the PHENIX Collaboration at RHIC. Her dissertation studied azimuthal correlation and conditional yield measurements in Au+Au, d+Au, and p+p collisions. After several years at Brookhaven National Laboratory as a postdoc, assistant, and associate physicist, she joined the faculty in the Department of Physics at the University of Illinois as an assistant professor in 2014. She continues to do research in the field of relativistic heavy-ion collisions as a member of the ATLAS Collaboration at the LHC at CERN and the PHENIX Experiment at the RHIC at Brookhaven.

P.J. Paul J LeBlanc
CSE-ICON and
Anadarko Petroleum
Corporation

Paul J. (PJ) LeBlanc was an applied mathematics major at Spring Hill College, a small, liberal arts college in Mobile, Alabama, that had a few physics courses but did not offer a separate physics degree. His physics professor suggested applying for an REU program and personally contacted the REU Director at University of Notre Dame to recommend PJ for the program. According to PJ, "My experience as an REU at Notre Dame literally changed my life. Because of Notre Dame's small laboratory setting, I was able to get a large amount of hands-on experience in a short amount of time. And I was hooked." He returned to Notre Dame for graduate school and finished his Ph. D., working in the area of nuclear astrophysics. After obtaining his Ph.D., PJ worked as a research scientist with Canberra Industries. He explored new neutron detection technologies and non-destructive assay techniques with a focus on radiological waste characterization. He was also involved in several projects related to the Fukushima nuclear reactor events in Japan. PJ currently works in the oil and gas industry with a focus on developing custom applications and scripts for optimizing oil and gas well production using a variety of statistical algorithms.

traditionally under-represented backgrounds and may not have been introduced to the full spectrum of opportunities that foster their success in Ph.D. studies in nuclear science. Therefore, there has been an expansion of programs that bridge the undergraduate and Ph.D. programs. Since 2006 Vanderbilt and Fisk Universities have hosted a highly successful bridge program, including an alumnus in nuclear theory. M.I.T. and Columbia also host bridge programs. More recently, the American Physical Society (APS) coordinates a bridge program that provides financial support for bridge sites at three universities with nuclear physics Ph.D. programs. About 20 universities with nuclear physics programs are affiliated with the APS program.

OUTREACH TO SCHOOLS AND THE PUBLIC—COMMUNICATING EXCITEMENT IN NUCLEAR SCIENCE

The need for a strong scientific workforce is not unique to nuclear science. The future health of many scientific fields, and the nuclear science enterprise in particular, depends on the continuous flow of talented, early career professionals into the field at all levels. Furthermore, these professionals must better represent the diversity of our society to ensure the field is attracting and retaining the best minds for continued success in fundamental and applied research and technologies and meeting the national needs in medicine, energy, security, and economic growth.

Diversifying the workforce in nuclear science requires that the entry pathways be broadened. It is important to encourage undergraduate students to enter nuclear science because the number of students earning bachelor's degrees in physics has not kept pace with the explosion of degrees granted in science, technology, engineering, and mathematics (STEM) fields since 1970. Data collected by the Integrated Postsecondary Education Data System show that while the number of degrees in all STEM fields more than doubled, by 2012 the number of physics degrees increased by only 30%. Further, physics trails all STEM disciplines in the percentage of degrees obtained by underrepresented minorities.

To attract the most talented students from the full spectrum of backgrounds, nuclear science programs must reach out to schools serving traditionally underrepresented groups, ensuring that promising students are aware of the exciting opportunities made possible by a career in physics and encouraging students to study science and math in high school and college. This is a long-term effort that can provide long-term rewards to the students and to the field, and these efforts must be valued, encouraged, and sustained.

It is just as important that members of the general public recognize and value both basic and applied research in nuclear science. Many members of the nuclear science community recognize these needs and are working to address them locally and regionally through outreach efforts to the public and to K–12 educators and students. The 2007 white paper, *A Vision for Nuclear Science Education and Outreach for the Next Long Range Plan*, and the 2015 white paper, *Nuclear Science Education and Innovation*, highlight many excellent examples of a wide range of activities developed to educate the public and excite K–12 students about nuclear science. One example is the Nuclear Science Wall Chart, which was developed by the Contemporary Physics Education Project at Lawrence Berkeley National Laboratory. It has been widely distributed to the schools and the public.

The nuclear science community has also taken advantage of its powerful accelerators and impressive experimental equipment for outreach activities. These invaluable assets are showcased at open houses and tours that typically draw large audiences and provide visual confirmation of the technical complexity and large scale of nuclear science research and technologies. Annually about 11,000 people visit RHIC at BNL on Long Island, the Thomas Jefferson Laboratory in Virginia and the National Superconducting Cyclotron Laboratory in Michigan on scheduled tours. In addition, the 2014 Neutrino Day at the Sanford Underground Research Facility in South Dakota drew more than 1,000 visitors.

In addition to facility tours, many activities that do not necessarily rely on accelerators and large laboratories are being organized to engage K–12 students and the general public. Examples include public lecture events, such as the Science Happy Hour at Yale, the Science Café at Brookhaven National Lab, and Saturday Morning Physics at Texas A&M and Florida State Universities. Activities specifically engaging children are the Art 2 Science program (NSF-supported Joint Institute for Nuclear Astrophysics), merit badge events for Boy and Girl Scouts (Lawrence Berkeley National Lab, Triangle Universities Nuclear Laboratory, and the University of Notre Dame), and a Physics Olympiad (Richmond University) (see Sidebar 8.2).

Sidebar 8.2: Highlights of Nuclear Science Outreach to Students and the Public

The white paper *Nuclear Science Education and Innovation* provides a comprehensive overview of education and outreach efforts in nuclear science.

The Thomas Jefferson National Laboratory annually hosts an open house for the general public.

Brookhaven National Laboratory hosts summer courses for high school students.

The Joint Institute for Nuclear Astrophysics hosts "The Physics of Atomic Nuclei (PAN@IMSA)" program at the Illinois Mathematics and Science Academy in Aurora, Illinois. This effort is supported in part by the National Science Foundation.

Nuclear scientists at Notre Dame and JINA have developed a new Girl Scout badge, "Getting to Know Nuclear," tailored for young women, which covers nuclear science and societal applications.

Neutrino Day is an annual science festival held in the Lead, South Dakota community, hosted by the Sanford Underground Research Facility.

Every summer the RHIC at BNL hosts "Summer Sunday: Atom-Smashing Fun."

Hope College hosts the Nuclear Forensics Investigations Summer Science Academy.

Other events are specifically designed to increase the participation of traditionally underrepresented minorities, such as the Nuclear Science Lab Field Trips at the University of Notre Dame and Michigan State University and the BEAMS (Becoming Enthusiastic About Math and Science) program at Jefferson Lab. Triangle University Nuclear Laboratory (TUNL) faculty members participate in K-12 school programs in the North Carolina Triangle area, with large numbers of students from underrepresented minorities. Models for successful outreach to students from diverse backgrounds include Professor Jorge Lopez from the University of Texas-El Paso and Dr. Ben Zeidman from Argonne National Laboratory, who were recognized in 2014 and 2013, respectively, with the DNP Mentoring Award for outstanding contributions to mentoring nuclear physics students from underrepresented backgrounds.

Social media sites also provide a platform for the nuclear science community to engage the general public. In order to communicate effectively, it is important to capitalize on these existing and popular sites to reach a science-interested audience. Outreach coordinators at BNL, JLab, LBNL, the National Superconducting Cyclotron Laboratory, and the Joint Institute for Nuclear Astrophysics, for example, have all used social media sites, such as YouTube, Facebook, Twitter, and Pinterest, to engage the general public, school teachers, and students. These sites provide the opportunity for interactions that go beyond just the posting of information. They can lead to an open dialog with the public about the research activities of these organizations. For those in the tech-savvy public who want to learn more about nuclear physics research, there is a mobile app, "Live Chart of Nuclides," that is an interactive chart of atomic nuclei distributed by the International Atomic Energy Agency.

SUMMARY

This chapter has summarized the workforce trained in nuclear science, challenges in growing this workforce to meet the Nation's needs, some of the innovations in graduate and postdoctoral education, and the critical role that undergraduate research plays in attracting future leaders in nuclear science.

The U.S. needs a highly educated and trained workforce for fundamental and applied research in nuclear science and its associated technologies. Meeting the Nation's

need for this highly trained workforce relies critically on recruiting and educating early career scientists. The data displayed in Figure 8.2 show that the total number of Ph.D. graduates in nuclear science has been flat for the past decade. This is consistent with the U.S. continuing to attract the best and brightest students from the U.S. and around the world for graduate studies and research. However, compared to the patterns 10 years ago, a higher percentage of nuclear physics faculty at universities and national laboratories and faculty recipients of prestigious early career awards received their Ph.D.s from universities outside of the U.S. These data indicate that the delicate balance between nurturing U.S. students for leadership positions in nuclear science and attracting the most talented early career scientists from around the world may no longer be in effect. Increasingly, to meet the demands for the most talented nuclear scientists for positions in universities and national laboratories, these individuals have been recruited to the U.S. after their doctoral studies. The 2014 NSAC report, *Assessment of Workforce Development Needs in the Office of Nuclear Physics Research Disciplines*, identified a continuing vital need to enhance the development of a talented U.S. workforce by increasing the participation of U.S. students in the opportunities in fundamental and applied nuclear science.

This requires opportunities for undergraduate students to be engaged in forefront research and studies in nuclear science. Graduate students are also inspired by highly visible postdoctoral opportunities to which they can aspire.

We recommend that the NSF and DOE take the following steps.

- **Enhance programs, such as REU, SULI, and the SSNR, that introduce undergraduate students to career opportunities in nuclear science.**

- **Support educational initiatives and advanced summer schools, such as the NNPSS, designed to enhance graduate student and postdoctoral instruction.**

- **Support the creation of a prestigious fellowship program designed to enhance the visibility of outstanding postdoctoral researchers across the field of nuclear science.**

9. Broader Impacts

In addition to its primary goals to elucidate the atomic nucleus and fundamental forces and symmetries, research in nuclear science has for decades had a strong impact on chemistry, biology, medicine, and computational science. Nuclear science research has resulted in many practical applications of importance to human health, economic growth, space exploration, and national security through the use of radioisotopes, applications of particle accelerators and radiotracers, and advances in radiation detection and measurement. This chapter presents the broader impacts of nuclear science. Practical applications of isotopes and nuclear technologies in health care and national defense and security are first highlighted, followed by briefer discussions of broader impacts in other nuclear science applications and also connections to other scientific disciplines.

USE OF ISOTOPES

Nuclear science research has produced a wide range of stable and radioactive isotopes that have a multitude of applications. Since 2009, the Office of Nuclear Physics has been responsible for the DOE Isotope Program (formally the Isotope Development for Production, Research, and Applications, IDPRA, program). The Isotope Program supports both the production and the development of production techniques for radioactive and stable isotopes that are in short supply for research and applications. Isotopes are high-priority commodities that have strategic importance for the Nation and that are essential for energy, medical, and national security applications, as well as for basic research. The primary goal of the program is to make critical isotopes more readily available to meet domestic U.S. needs. The Isotope Program traces its roots to the Manhattan Project, and one of its first products was ^{14}C, which is used in carbon dating. Today a variety of isotopes is produced or distributed by the Isotope Program, including both radioisotopes and stable isotopes.

Numerous applications require radioisotopes. Perhaps the most evident are those used in medical diagnostics such as ^{18}F in PET imaging for clinical diagnosis of cancers (Sidebar 9.1). Because of its short half-life, ^{18}F is produced in small cyclotrons that are available and installed at or near hospitals across the country. The development of the accelerator techniques to produce

^{18}F represents a significant spinoff of nuclear physics techniques. Another important isotope that is produced in reactors is ^{99}Mo, which serves as the source of the most frequently used diagnostic isotope, ^{99m}Tc. The NNSA, through its Global Threat Reduction Initiative, is supporting commercial partners to develop ways of making ^{99}Mo domestically without the use of highly enriched uranium. A domestic source would reduce the risk of reliance on foreign nuclear reactors for its production. An isotope that can serve as a partial "stand-in" for ^{99m}Tc is ^{82}Rb, which is used to monitor lung and heart function. The main source of ^{82}Rb is from the beta decay of longer-lived ^{82}Sr. The Isotope Program currently produces much of the Nation's supply of ^{82}Sr, utilizing accelerator technology at both LANL and BNL.

One promising avenue of active R&D, both in isotope production and medical application, involves the use of alpha-emitters for cancer therapy. Nuclei such as ^{225}Ac and ^{223}Ra can be chemically placed at the cancer cell, and their decay by alpha emission releases significant energy to kill the cancer cells while reducing the damage to healthy tissue. Significant therapeutic progress was recently demonstrated with ^{223}Ra and led to Food and Drug Administration approval of this isotope for treatment of metastatic prostate cancers in bones. As another example, for several years ^{225}Ac has been milked from a ^{233}U "cow" for use in clinical trials aimed at reducing pain in metastasized breast cancers. Current ^{225}Ac production stands at 700 mCi/year, while its use as a therapeutic drug is expected to increase tenfold or more. In order to meet this demand, the Isotope Program currently funds R&D that uses proton bombardment of a ^{232}Th target at either LANL or BNL and chemical processing at ORNL to generate enough useable material for large-scale trials. It is hoped that a complete chemical process will be understood within the next few years.

The Isotope Program produces 70% of the world's supply of ^{252}Cf at HFIR at ORNL. Because of its high neutron yield, the nuclear industry uses ^{252}Cf as the neutron generator for reactor restarts, while the oil industry uses ^{252}Cf as an activation source in a variety of industrial applications including oil well logging. As a byproduct of ^{252}Cf production for industrial uses, ^{249}Bk has been produced for super-heavy element research,

Sidebar 9.1: Medical Isotopes for Imaging and Therapy
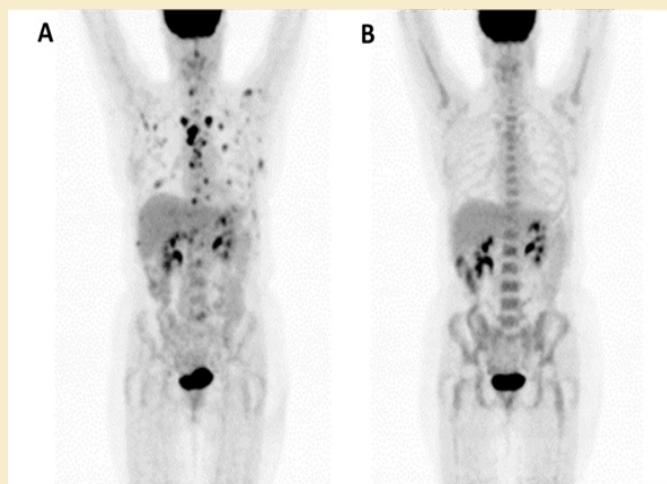
Radioisotopes are generally used to "label" a radiopharmaceutical. The overall chemical structure of the radiopharmaceutical determines its biological properties (e.g., targeting), while the radioisotope determines imaging or therapeutic properties. As diagnostic agents, isotopes emit radiation that allows specialists to image the extent of a disease's progress in the body, based on cellular function and physiology. This provides doctors with a better understanding of the diseased tissue than is available through other diagnostic procedures, which may only capture anatomical information. In particular, positron-emitting radionuclides, which can be incorporated into imaging agents, can provide sensitive and specific information about tumor physiology. As a therapeutic agent, this technique can deliver highly-targeted radiation to target tissue, while sparing side effects to normal tissues.

For example, the effectiveness of a cancer treatment can be determined early on with the radiolabeled glucose analogue, [^{18}F]fluorodeoxyglucose, [^{18}F]FDG, which measures changes in metabolic function of the tumor (see figure). Prior to the clinical use of this technology, patients and physicians had to wait much longer for changes to occur in the anatomical images. New imaging agents can also be used to prescreen patients who may or may not benefit from certain types of therapy, thus paving the way for precision and personalized medicine. Radiolabeled versions of antibodies, peptides, or nanoparticles can shed light on uptake of these therapeutic agents in certain types of tumors.

Advanced targeted therapies for cancer and other diseases have been developed using radionuclide approaches. Recently, an alpha-emitting isotope, ^{223}Ra, was approved by the Food and Drug Administration to treat advanced prostate cancer. Based on this success, other alpha-emitting agents are being investigated for treatment of a wide variety of cancers.

The use of monoclonal antibodies to direct radioisotopes to cancer cells, known as radioimmunotherapy, has enormous promise and versatility because nearly every cancer cell expresses antigen epitopes to which a reactive monoclonal antibody can be produced. In addition, one subclass of peptide-based targeted agents has demonstrated dramatic therapeutic efficacy against neuroendocrine tumors. In many of these cases, the challenge is often to provide sufficient quantities of the alpha-emitting radionuclides used in the clinical studies of these therapies. The use of isotope pairs for the development of agents that can be employed for imaging and therapy, "theragnostics," is also a promising path forward. These dual-function radiopharmaceuticals can play an important role in personalized medicine as they can be used to determine whether the prescribed therapeutic dose will work in a patient prior to administration.

[^{18}F] fluorodeoxyglucose scan of a woman diagnosed with T cell lymphoma. (A) At diagnosis, which shows uptake in extensive disease sites along with normal signal in the brain and bladder. (B) Following four months of chemotherapy, which shows the dramatic decrease in signal in the cancer sites, indicating that this patient is responding well to therapy. Image credit: J. McConathy.

and the CARIBU source (see Chapter 7) also utilizes ^{252}Cf. Many other significant examples of radioisotope use can be found in the NSAC report, *Meeting Isotope Needs and Capturing Opportunities for the Future: The 2015 Long Range Plan for the DOE-NP Isotope Program,* which includes a comprehensive study of

opportunities and provides priorities for isotope research and production that could be implemented by the Isotope Program. The research priorities identified in that report included continued support for R&D related to the production of alpha-emitting and theragnostic radioisotopes, support for the use of electron

accelerators for isotope production, and research and development in the targets to produce these isotopes. The report also recommended investments in the isotope production infrastructure at the national laboratories and FRIB as well as an expansion of the effort to work with university isotope production sites.

The Isotope Program is also responsible for stable isotope distribution within the U.S. Since 1995, the U.S. has not possessed the capability to produce stable isotopes and has been selling off its inventory of stable isotopes that were generated during the Cold War. Often, stable isotopes are the feedstock necessary to produce a medical radioisotope. For example, one can use ^{98}Mo as feedstock for the ^{99}Mo production discussed earlier. Since 2012, the Isotope Program has been funding the re-establishment of stable isotope production capability at the Enriched Stable Isotope Pilot Facility (ESIPF) at ORNL. ESIPF utilizes nuclear separation capabilities unique to the DOE and will, within the next two years, begin to restore a U.S. domestic supply of stable isotopes. An expansion of this capability could be applied to a variety of problems relevant to nuclear physics R&D, including enrichment of relevant neutrinoless double beta decay nuclei.

OTHER MEDICAL APPLICATIONS

Accelerator technology developed for basic physics applications also has made an impact in medicine. Several facilities are now using accelerated protons to treat cancer. In this application, the beam energy is adjusted so that the particle stops in the tumor, thus depositing a highly localized dose of radiation, killing the tumor while limiting exposure to the surrounding normal tissue. This approach is of especial importance in the treatment of pediatric cancers, brain tumors, and tumors near the spine, due to the precision with which the radiation can be delivered. Application of this technique using heavier particles such as carbon ions, which will deliver yet higher doses of highly localized energy deposition, is being investigated. Continued development in accelerator technology for particle therapy is needed in order to realize the full potential of this approach to cancer treatment. Additional details are provided in the sidebar: Nuclear Scientists Lead the Way on Proton Radiation Therapy (Sidebar 7.1) in Chapter 7, Facilities and Tools.

NATIONAL SECURITY

Nuclear science and technology play an important role in securing the Nation's borders. Cargo inspections and port security screenings are employed to detect dangerous materials at ports of entry. Such inspections must be both fast and accurate in order to efficiently detect targeted materials while not impeding workflow and must balance personal protection and privacy. An extensive network of radiation portal monitors is in place to prevent the illicit transport of radiological materials. These portals use nondestructive, passive methods that rely on the detection of gamma-rays and neutrons. Active interrogation, using combinations of small-scale accelerators and radioactive sources coupled to detector systems, serves as a second-tier protection against illicit transfer of nuclear materials. Many of the techniques and capabilities developed within nuclear physics are providing solutions to homeland security applications funded by the Department of Homeland Security (DHS) and within the NNSA.

Assuring the integrity of the Nation's nuclear arsenal is the primary mission of the NNSA through the Stockpile Stewardship programs. These programs often rely on important contributions from scientists trained while performing R&D within the Office of Nuclear Physics. An important broader impact of nuclear science is the development of a highly qualified workforce necessary to enable NNSA and DHS nuclear activities. Fundamental research in nuclear science provides the people and knowledge that may someday be applicable to problems associated with national security.

As an example of how information flows from nuclear science to applications, consider nuclear weapons testing. The U.S. ended its nuclear weapons testing program in 1992. Weapons tests that were conducted before the comprehensive test ban provided important data on the characteristics of nuclear explosions. Nuclear weapons' explosions are extremely complicated to simulate and require expertise in materials under extreme conditions, plasma physics, atomic physics, and shock propagation, among other topics. Nuclear burning networks are also important in understanding the explosions, and, here, nuclear data play a role. Some of the uncertainties in the weapons simulations continue to be reduced by gaining experimental knowledge on the detailed cross sections for neutrons and light charged particles interacting with both stable and radioactive

isotopes. Nuclear physicists have developed innovative, indirect approaches to infer the needed cross sections. The advent of new facilities producing radioactive nuclei in sufficient quantities to study the direct neutron capture will put such cross section measurements within reach.

The U.S. utilizes numerous monitoring systems to analyze nuclear threats. One challenge for existing monitoring systems is differentiating the potential threat agents from other sources that may trigger radiation detectors. For example, patients routinely receive radioactive isotopes to diagnose and treat their diseases; such individuals may trigger portal alarms or other monitoring equipment. Using nuclear spectro-scopic techniques, homeland security personnel can assess what isotope is present and determine whether it is acceptable to pass through the monitoring systems. In some cases, nuclear technicians provide expert backup capabilities when a detector has alarmed on an isotope that is not routinely seen in patients. The technicians provide an important service by expediently analyzing the detector data to determine whether the radioisotope is a potential threat.

OTHER APPLICATIONS

Radioisotope Dating

The use of radioisotopes to determine the age of an object is perhaps the most familiar application of radioactive nuclei to quantitative analysis. Radioisotope dating exploits the well-known features of radioactive decay kinetics to place objects in geological time. Early applications of radioisotope dating usually involved low background counting of the radioactive samples. More sophisticated techniques have been developed that provide high selectivity and sensitivity for both stable and radioactive rare isotopes. Accelerator Mass Spectrometry (AMS) is one of these techniques, where an accelerator is used to determine extremely low-level isotopic concentrations. Carbon-14 (^{14}C) is probably the best-known and one of the most widely-used radio-dating isotopes, due to the prevalence of carbon in living organisms. The decay half-life of ^{14}C of 5,730 years is well matched to the history of human activity. The high sensitivity of AMS has extended the application of radioisotope dating to long-lived isotopes (e.g., beryllium-10, aluminum-26, and iodine-129) that are amenable to the study of rocks and soils of geological significance. Noble gases offer another means for

assessing geophysical and geochemical phenomena. The abundance of argon-40 relative to argon-39 is used for dating rocks and minerals based on the natural radioactive decay of potassium-40 and neutron-induced reactions on potassium-39. The argon-argon technique is applicable to geological samples over a broad time span, from as young as 2,000 years to as old as the earth itself. The quantitative analysis of noble gas concentrates at the part-per-trillion level has been achieved using the method of atom trap trace analysis. For example, krypton-81 concentrations were measured in saline groundwater from wells near the Waste Isolation Pilot Plant (WIPP) to validate groundwater flow models.

Elemental Analysis

Quantitative isotope analysis is not limited to radioisotopes. Stable isotope ratios, determined through the measurement of isotopic mass distribu-tions, can provide insight into environmental factors that influenced the sample. For example, the determination of stable isotope ratios of oxygen and hydrogen in human hair was found to be correlated with geographic location within the U.S., which has significant forensic applications. Several radioanalytical methods are available for trace elemental analysis, such as particle-induced X-ray emission (PIXE), particle-induced gamma-ray emission (PIGE), Rutherford backscattering (RBS), and neutron activation analysis (NAA). The methods are nondestructive, that is, the sample is not consumed in the measurement, and each provides unique capabilities to characterize the composition of the sample. PIXE involves the analysis of characteristic X-rays emitted from atoms that are excited by proton irradiation and is applicable to elements from sodium to uranium (Sidebar 9.2). PIGE also involves the use of protons to excite nuclei; however, characteristic gamma-rays are analyzed. PIGE is used to examine light elements such as lithium, boron, and fluorine, which are difficult to access by other techniques. RBS is a method whereby the composition of materials is determined by the scattering of ions at backward angles to the incident beam. The backscattering not only provides details on composition but also gives a depth profile of the elemental constituents. In NAA, neutrons are captured by materials, and the material composition is deter-mined from the resulting photon radiation. The applica-tion of neutrons and detection of photons, both of which can readily traverse through materials, makes

Sidebar 9.2: Nuclear Science in Art and Archaeology

Nondestructive nuclear techniques are key to analyzing priceless historical artifacts and works of art. The *Hidden Treasures of Rome Project* makes use of X-ray fluorescence (XRF) and neutron activation analysis (NAA) to examine valuable and rare specimens without damaging the material. The project is examining never-before-studied historical items dating back to before the founding of Rome and is carried out in a collaboration involving the city of Rome, the Capitoline Museum, the Italian and American governments, Enel Green Power, and the University of Missouri. The main artifacts under study are black-glazed pottery from this time period. The chemistry of each pot is compared to extensive databases to allow archaeologists to determine where each individual vessel was produced, making it possible to reconstruct patterns of trade and social interactions in ancient Rome. Researchers at the Missouri University Research Reactor have completed XRF studies on these artifacts and have been able to identify iron-based compounds in the glaze (Figure 1). Because NAA is more sensitive and probes the interior of larger volume samples, it will likely reveal much more about the pottery, and any differences may indicate a different origin for some of the pots. Many students from the University of Missouri's Department of Art History and Archaeology are directly involved in this research project. After the study, the objects will be returned to Italy.

Some laboratories have deployed accelerator systems primarily for the forensic analysis of art and archaeological artifacts. As highlighted in a *Physics Today* feature article, these accelerators allow scientists and art historians not only to look below a painting's or an artifact's surface, but also to analyze in detail the pigments used, to investigate painting techniques and modifications done by the artist or by art restorers, to find trace materials that reveal ages and provenances, and more. Those techniques can provide a slew of information to help substantiate or negate the authenticity of an artwork or artifact, and they also furnish information essential for careful restoration and preservation. At the University of Notre Dame, researchers use proton-induced X-ray emission (PIXE) and accelerator mass spectroscopy (AMS) to study artifacts brought by local archeologists, as well as items from the Snite Museum of Art's extensive collection of Mesoamerican figurines and Arts of Native Americans, which features ceramics from prehistoric times in the American Southwest (Figure 2). The researchers have brought their research findings to the classroom. An undergraduate physics class at Notre Dame, Physical Methods in Art and Archaeology, attracts students from many different fields and covers topics such as X-ray fluorescence and X-ray absorption, proton-induced X-ray emission, neutron-induced activation analysis, radiocarbon dating, accelerator mass spectroscopy, luminescence dating, and methods of archeometry.

Figure 1: *A University of Missouri researcher characterizing an ancient Roman artifact (photo credit Nic Brenner, University of Missouri).*

Figure 2: *Figurine found in Mesoamerican burial grounds and currently housed at the University of Notre Dame's Snite Museum of Art. The figurine is mounted on the proton-induced X-ray emission (PIXE) beam line at Notre Dame's 11-MV electrostatic accelerator to obtain quantitative details of the pigment composition; in particular, PIXE reveals the iron and manganese content of the paint.*

NAA amenable to trace element analysis in complex matrices. Slow-moving neutrons experience a strong, selective interaction with the surface layer of materials. Such cold or ultracold neutrons serve as a unique probe of surface elemental composition and the dynamics of surface layers. These nondestructive, trace analysis methods have demonstrated uses in industry (consumer product screening), applied science (analysis of Antarctic meteorites), and fundamental science (self-ordering of nanotubes).

Accelerator Innovation and Application

Another application of accelerators, beyond the radioanalytical analyses and AMS described above, is in the purposeful modification of materials. Implanting ions in a specific surface pattern and depth can alter material properties and improve material performance. This practice is best exemplified in the application of accelerators in the semiconductor industry to infuse materials with dopants. Accelerator beam treatment of superconductors has also demonstrated improved material properties. Small voids can be introduced into high critical temperature ceramic superconductors by ion beam bombardment. These voids act as strong pinning centers, preventing the degradation of the resistance and critical current density of the superconductor.

Accelerators, as well as radioisotopes, play an important role in destroying food- and water-borne pathogens, thus protecting human health. The U.S. has one of the largest food irradiation industries in the world. Gamma- and X-ray radiation sources are most commonly used because of their greater penetration power, but high-energy electron beams from accelerators are used as well. High-energy electron beams are also effective in decontaminating wastewater, both with respect to microbial contamination and most common organic pollutants. More widespread implementation of this technology at present is impeded by large infrastructure costs.

Energy

The increasing world demand for energy, along with concerns about the availability and environmental impact of fossil fuels, has brought calls for a renewed investment in nuclear power. In 2013, 20% of the U.S. electricity demand was provided by 99 reactors that generated nearly 800 billion kilowatt-hours of electricity. Nearly all these reactors have received or applied for

20-year license renewals, ensuring sustained operations for the near term. There has also been a significant uprating of existing nuclear power plants since 2000, with capacity equivalent to six additional reactors. Meanwhile, five nuclear power plants are currently under construction, with plans for another 12 new plants under active review by the NRC. The role of nuclear science in the nuclear power industry is multifaceted and includes research on the nuclear fuel cycle, improved storage and monitoring of used nuclear fuel, environmental monitoring, and more complete and accurate data on the fission and neutron absorption processes. The latter activity is supported by the National Nuclear Data Program, which serves as the steward for reaction and decay data needed to properly model nuclear energy production, in addition to supporting nuclear science and national security needs.

One consideration for license renewals of operating plants is the sustainability of existing infrastructure. The integrity and performance of structural materials experiencing long-term exposure to high-radiation fields is an active area of research. Radiation damage in the reactor environment can be mimicked by high-intensity ion beams. The damage observed in these studies as a function of dose is used to improve computational models that simulate radiation-matter interactions. Such efforts are important, both for efficient plant operations and for improving designs for future power reactors.

Nuclear science and technology are also employed in energy exploration activities. Sealed radioactive sources are routinely used to evaluate hydraulically fractured and nonfractured wells. Gamma-ray sources, such as cesium-137, are used to determine the density of a rock formation, and neutron sources are used to assess the porosity of the formation. Radiotracers are also used in either gas or liquid form to determine flow rates at the well head.

Nuclear batteries are essential for deep space missions. Spacecraft use thermoelectric generators to power the electronics on board. Current nuclear battery research has focused on two areas. The first is identifying radionuclides that can power sensor systems without generating a sensor response themselves. Once identified, these radionuclides will need to be produced in quantities beyond the current level of production for research. Research and development also continues into new radioactive power sources that are made

from nonfissile isotopes, which are safer in the event of launch malfunctions.

The development of miniaturized nuclear batteries has been motivated by the need to power micro-electrome-chanical systems (MEMS). MEMS are the microscopic structures integrated in silicon that combine mechan-ical, optical, and fluidic elements with electronics. They have been developed for use as thermal, magnetic, and optical sensors and actuators; as micro-chemical analysis systems; as wireless communication systems; and as biomedical devices. The ability to employ these systems as portable, stand-alone devices in both normal and extreme environments depends, however, upon the development of power sources that can provide the necessary power for a machine that is smaller than a dust mite. Nuclear batteries are the optimal solution to this problem since the energy density of radioactive material is approximately one million times greater than that of lithium ion batteries. Recent technological advances enable the production of miniaturized nuclear batteries that convert the energy of alpha particles and beta particles emitted in radioactive decay into useable electrical power. In contrast to chemical-based power sources and photovoltaics, nuclear batteries can operate for extended periods of time and in extreme environments.

SCIENCE CONNECTIONS

Nuclear science shares common threads with many other scientific disciplines. The breadth of the field is rooted in the fact that the atomic nucleus and its constituent particles have impact on natural phenom-ena over wide ranges of time and space. In addition, atomic nuclei offer a unique laboratory to study complex few- and many-body systems that bridge the domains of microscopic and macroscopic physics. Specific examples of connections to astrophysics, atomic physics, high energy physics, computational science, and complex quantum systems are highlighted below.

Astrophysics

The connections of nuclear physics and astrophysics are numerous, and many of these connections are discussed in Chapter 4 of this Long Range Plan, Nuclear Astrophysics. Nuclear physics is an essential component of nucleosynthesis that allows it to be used as a probe for stars and stellar processes. All types of supernovae are influenced by nuclear physics. Nuclear reactions

drive the early evolution of the progenitors of superno-vae, and the reaction remnants left behind by those nuclear processes are eventually scattered in the interstellar medium. Type Ia supernovae, while being important nucleosynthesis sites, also play a primary role in cosmology as standard candles for very large cosmic distance measurements. Progenitors and properties of Type Ia supernovae, including the underlying nuclear physics, need to be understood to gauge, for example, the systematic errors associated with such distance measurements.

Neutron stars also play a central role in nuclear astro-physics (see Sidebars 3.2, 4.2, and 4.3). They serve as the engines of core-collapse supernovae and neutron star mergers, yet a consistent picture of the nature of neutron stars, and the nuclear physics that governs them, remains elusive. Core-collapse supernovae and neutron star mergers are the likely providers of neutron-rich matter for the rapid neutron capture process (r-process), responsible for the origin of the heavy elements. The nuclear equation of state and neutrino interactions in supernovae affect the dynamics of both core collapse and mergers, but their full role remains to be systematically explored.

Neutrinos play a special role in astrophysics, and understanding their role in nucleosynthesis, superno-vae, and neutron stars is critical. Solar neutrinos can be used to infer the main source of the sun's energy: the nuclear fusion of hydrogen into helium through a chain of proton-proton (pp) reactions. Borexino, a third-generation solar neutrino detector that employs a 300-ton liquid scintillator, was developed to detect solar neutrinos by their elastic scattering on electrons (Sidebar 9.3). It was able to obtain measurements of solar neutrinos emitted in nearly all of the nuclear reactions that generate the sun's energy. The agreement between the energy produced by nuclear reactions (inferred from neutrinos) and the energy determined from the radiant luminosity implies that the sun's power is unchanged during the time-delay between energy production in the core and radiant emission from the surface, estimated to be approximately 100,000 years.

Complex Systems

Complex many-body quantum systems are the mainstay of many areas of science, from condensed matter physics to quantum chemistry (Sidebar 9.4) and

Sidebar 9.3: Neutrinos from the Sun

Borexino is a third-generation solar neutrino detector that employs a 300-ton liquid scintillator to detect solar neutrinos by their elastic scattering on electrons (see figure). Unlike earlier detectors, it has a low threshold energy and is sensitive to all neutrino sources. Its signature feature is an ultralow background that allows the energy spectrum of each type of neutrino to be distinguished from background.

Since operations commenced in 2007 at the Gran Sasso underground laboratory in Italy, the detector has yielded measurements of solar neutrinos emitted in nearly all of the nuclear reactions that produce the sun's energy. The 0.86-MeV ^{7}Be neutrino was the first to be measured, followed by measurements of pep neutrinos and ^{8}B neutrinos.

In 2014, the Borexino collaboration published a measurement of the "pp" neutrinos. They are produced in the reaction, $p + p \rightarrow d + e^+ + \nu$, the first step in the pp-chain of reactions that produces the sun's energy by converting four protons into helium-4. The pp neutrinos have a maximum energy of 440 keV and impart a maximum energy of 264 keV to electrons by elastic scattering. They account for 90% of the sun's neutrinos, but detecting their low-energy signals was challenging due to backgrounds at low energy.
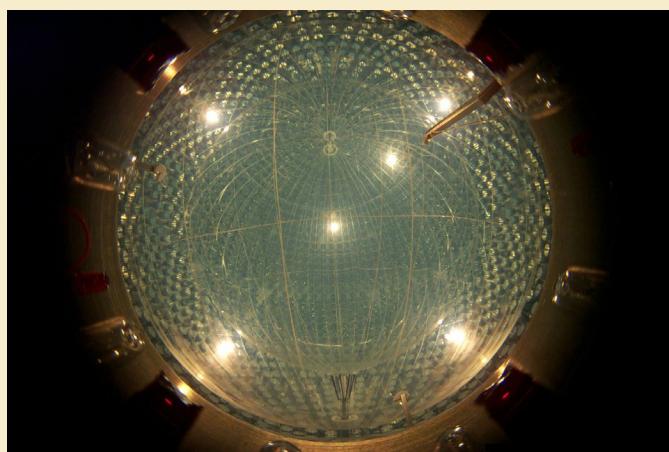
The measurements of the four solar neutrino fluxes, each with different energy and from a different stage of the pp chain, provide a more complete understanding of the sun and neutrinos. First, the results clearly demonstrate that the main source of the sun's energy is nuclear fusion of hydrogen into helium through the pp-chain of reactions. Second, the agreement between the energy produced by nuclear reactions (inferred from neutrinos) and the energy determined from the radiant luminosity

implies that the sun's power is unchanged during the time delay between energy production and radiant emission, estimated to be ~10^5 years. Third, the evidence for neutrino oscillations is confirmed in all the neutrino branches, and the data provide new evidence for the transition from vacuum oscillations (pp) to "matter effect" oscillations (^{8}B).

Borexino demonstrated the feasibility of ultralow backgrounds and the power of spectral measurements by determining the flux of each neutrino branch in the pp-chain. This result is a milestone in low-background counting that shows what might be possible for other rare event research, such as detection of dark matter or neutrinoless double beta decay. For solar neutrinos, the next challenge is a measurement of neutrinos from the CNO cycle that will address the "metallicity problem," the abundance of these elements in the sun.

The Borexino detector in the Gran Sasso underground laboratory in Italy.

biophysics. The unusual emergent properties of many of these systems can be traced back to subtle quantum correlations among their components, often described as entanglement. Nuclear physicists have contributed many advances to our understanding of these systems, especially of complex quantum systems that are strongly coupled at the microscopic level.

Developing a quantitative understanding of strongly-

paired Fermi systems is important since they offer a unique regime for quantum many-body physics, relevant in very different physical settings including cold Fermi atoms and neutron stars. Nuclear physicists have made important contributions to the theory of cold Fermi gases. They have provided some of the earliest and most accurate calculations of many of the universal parameters describing the Unitary Fermi Gas (fermions with a zero-range interaction with an infinite scattering

length). The most accurate results for the contact parameter describing the equation of state (the probability of spin-up and spin-down fermions at the same point), the pairing gap, and the critical temperature from the superfluid to the normal fluid have all been obtained by nuclear physicists. These properties are all closely related to important aspects of nuclear physics (e.g., cold Fermi gas at unitarity has many features in common with diluted neutron matter). Nuclear physicists have correctly described the vortex dynamics in superfluid Fermi gases, providing realistic results for finite systems, including pairing and shell closure, and studying shear viscosity in these strongly correlated systems.

One of the most conspicuous breakthroughs made over the past decade is the application of the holographic gauge-gravity duality principle, originally conceived by string theorists, to real-world quantum systems such as quark-gluon plasma. Nuclear theorists have played a leading role in showing how these techniques can be used to calculate dynamical properties of strongly coupled quantum systems that are not accessible by any other rigorous methods. Examples include calculations of dissipation in a flowing liquid or how such systems thermalize when they are created far out of equilibrium and how they respond to time-dependent external perturbations. These methods, honed on nuclear physics challenges, are now being applied to many-electron or many-spin quantum systems in condensed matter physics that are strongly coupled or strongly entangled or both. They have led to solvable models that have cast new light on strongly coupled non-Fermi liquids, strange metals, strongly coupled superconductors, quantum phase transitions, and quantum critical transport. They are being used to face the challenges of understanding strongly coupled fluids with no known particle-by-particle description, challenges that are central to contemporary condensed matter physics. They have also been applied to the study of turbulence, for example, to show for the first time that in a turbulent superfluid thin film the energy cascades from large length scales down through smaller and smaller whirls and eddies—like in ordinary 3D turbulence but opposite to the behavior of an ordinary thin film.

Nuclear physicists have also played a pioneering role in elucidating the anomalous properties of chiral quantum systems. The chiral magnetic effect and the chiral vortical effect, which were first identified as dynamical properties of quark-gluon plasma, are particularly interesting because they can be understood as local violations of fundamental symmetries of space-time. The chiral magnetic effect has recently been discovered in experimental measurements on $ZrTe_5$ that were prompted by ideas formulated under the guise of nuclear physics. Three other crystalline solids are now known to share the special property that electrons within them satisfy the same equations that govern left- and right-handed quarks in QCD. In these materials, the chiral magnetic effect is the observation that when a magnetic field is applied parallel to the direction in which an electric current is flowing, the current grows with the square of the magnetic field. This phenomenon is the opposite of giant magnetoresistance, a phenomenon seen in other materials whose discovery was recognized with the 2007 Nobel Prize in Physics.

Many-body systems composed of identical fermions are notoriously difficult to solve because of the so-called sign problem. In recent years, nuclear theorists have made significant advances on finding either rigorous or systematic practical solutions to such problems. For example, nuclear physicists have extended density functional theory to the description of many-body systems without external potentials. The combination of density functional theory with effective field theory promises not only a general theory of complex nuclei across the periodic table but also puts a model-independent solution of the structure of collapsed stars within reach. Another example is the fermion bag approach that provides for a reformulation of certain many-body systems in which the sign problem is absent, thus permitting numerical solution with arbitrary precision. These advances have applications in all areas of physics in which many-fermion systems are of interest.

Computational Science

The absence of any controlled analytical approaches for the solution of QCD in the confinement domain has forced nuclear and particle physicists to develop an *ab-initio* numerical technique: lattice gauge (LQCD) theory. Over the past decade, with the availability of peta-flop computers and improvements of algorithms, LQCD theorists have succeeded in calculating the hadron mass spectrum and many static properties of the proton from first principles, reaching few-percent accuracy (Sidebar 2.1). They have also succeeded in calculating the equation of state of quark-gluon matter with similar precision. The techniques developed in

order to make these advances have had an impact that reaches far beyond nuclear science. For example, novel computer architectures first realized by LQCD theorists have allowed U.S. computer manufacturers to regain world leadership in capability computing. The know-how in the use of field programmable gate arrays and graphics cards for the low-cost solution of extremely CPU-intensive, repetitive computations has attracted the interest of commercial companies. Over the next decade, LQCD theorists from the nuclear and particle physics communities stand ready to lead the transition of computational science into the exa-flop era. A broader discussion of exascale computing is presented in Sidebar 7.3: Towards the Future: Exascale Computing.

Advancement of many frontier questions in nuclear physics is predicated on the capabilities to build realistic models of complex systems and phenomena. Having this capability requires investments in both computer hardware and in development of algorithms to optimize the computing power to specific problems. The Scientific Discovery through Advanced Computing (SciDAC) initiative, funded by the DOE, provides the computational infrastructure that is enabling researchers to make significant advances in nuclear physics research in, for example, LQCD, nuclear astrophysics, and nuclear structure, as well as in areas of broader societal relevance, including fusion energy science, climate modeling, and combustion.

The mutually beneficial collaborations between ASCR's SciDAC Institutes and nuclear scientists, through the SciDAC-3 program, have led to important computational algorithmic developments critical to both research missions. An example is the advances in complex solvers essential to quantum mechanical calculations, such as multigrid algorithms. Another example is the work on uncertainty quantification in nuclear modeling that is of critical importance for building predictive capability.

Multidimensional hydrodynamics calculations are critical for advancing the understanding of stellar explosions, high-energy nuclear collisions, and the detonation of nuclear weapons. Nuclear astrophysicists exploit state-of-the-art numerical methods from multidimensional computational fluid dynamics to model, for example, the physics of thermonuclear supernovae and the hydrodynamics associated with the collapse of stellar cores to neutron stars. Nuclear physicists are using state-of-the-art dynamical modeling of relativistic heavy-

ion collisions to achieve a hydrodynamic description of quark–gluon plasma. Weapons scientists must produce a high-resolution representation of real explosive events, as nature would unfold them. The hydrodynamic simulations carried out are often driven by input data that was derived from weapons tests conducted in past decades.

Another area where know-how developed at nuclear physics facilities helps address challenging problems in other sciences is digital data management. Scientists at Thomas Jefferson National Accelerator Facility are helping NASA deal with the data challenges of their earth studies program that aims to use data gathered by satellites to explore global environmental effects. Scientists at the RHIC Computing Facility are helping condensed matter and astronomers deal with the vastly increased data that will be generated by the next generation of light sources and survey telescopes. Nuclear theorists apply new tools, developed for unbiased complex model-to-data comparisons, to other fields such as astrophysics that are faced with similar problems.

Atomic Physics

One link between atomic physics, particle physics, and nuclear physics that has already been discussed is the so-called "proton radius puzzle." There is a difference between radius values measured in a hydrogen atom, formed by an electron and a proton, and a muonic hydrogen atom, formed by a muon and a proton, which may indicate a hitherto unknown difference between the interactions of electrons and muons with the proton. Hydrogen offers a unique case study, as precise calculations based on QED theory can be carried out. By measuring the Lamb shifts to the energy levels in hydrogen atoms, the radius of the proton has been determined to be 0.88 femtometers (fm). Recent measurements used muonic hydrogen to improve the precision of the determination of the proton's size. The muon is identical to an electron, apart from being 200 times more massive. Because of its greater mass, the muon has a much smaller orbit and thus, much stronger interactions with the proton. Measurements of the Lamb shift in muonic hydrogen show a radius of 0.84 fm, 4% smaller than the measurements using the ordinary hydrogen atom. The new result suggests that the volume of the proton is 13% smaller, and the density is 13% higher than previously believed. Several attempts to

Sidebar 9.4: Periodic Behavior of the Heaviest Elements

Elements at the end of the periodic table are not found in nature because they are much more unstable than their lighter counterparts. The chemistry of the superheavy elements and our quest to expand the periodic table and its expanded counterpart, the chart of the nuclides, is an important area of basic science (see figure). This is illustrated by the high degree of international participation in this area of study. The two newly-discovered superheavy elements were recently named flerovium (Fl, Z = 114) and livermorium (Lv, Z = 116), after nuclear science laboratories in Russia and the U.S., respectively. The chemistry of elements in this mass range is dominated by relativistic effects, thus the behavior of these new species is not always predictable.

Rapid physical and chemical techniques developed for nuclear science can help determine the chemistry of these new elements, leading to insights about the fundamental nuclear and electronic structure. These techniques rely on measurements of the volatility of compounds of the superheavy elements to determine their appropriate placement within the period table. To date, flerovium is the heaviest element with which chemical experiments have been performed. Studies investigating the behavior of flerovium and its decay product copernicium (Cn, Z = 112), carried out in international collaborations, suggest that while flerovium is more inert than lead and may exist as a volatile species, it still maintains metallic characteristics.

Periodic table of the elements. Chemical characterization has been carried out to element flerovium (Fl, Z=114).

improve Lamb shift measurements in ordinary hydrogen, along with new measurements of the radius in electron scattering, are ongoing with the aim to resolve this puzzle.

Efforts have begun to make the first direct comparison of electron and muon scattering from the proton to see if the observation of the smaller proton radius deduced from muonic hydrogen is duplicated in scattering with muons. This would be the most direct evidence for a

breakdown of the Standard Model assumption that, apart from the difference in mass, electrons and muons have identical properties and interactions.

Nuclear and atomic physicists have joined forces to search for permanent electric dipole moments (EDMs) of the neutron, atoms, and molecules, as discussed in Chapter 5 of this report, Fundamental Symmetries and Neutrinos. EDMs offer a promising avenue towards physics beyond the Standard Model through the

violation of both time-reversal and parity symmetries. These searches rely on nuclear physics' expertise and facilities, particularly in the making and manipulation of ultracold neutrons, and on the availability of radioactive atoms of the elements radium, radon, and francium, whose deformed nuclei are predicted to greatly amplify EDMs. The experimental EDM efforts employ precision measurement techniques and calculations developed in atomic and molecular physics.

High Energy Physics

The study of neutrinoless double beta decay offers another means for low-energy nuclear science to contribute to the quest for physics beyond the Standard Model as described in Chapter 5. The observation of this process would simultaneously demonstrate that lepton number is not conserved and also that the neutrino is a massive Majorana fermion, that is, its own antiparticle. In neutrinoless double beta decay, the atomic nucleus acts as a probe of lepton nonconserving interactions amongst the fundamental constituents of matter, namely quarks, electrons, and neutrinos. If a nonzero rate is observed in future neutrinoless double beta decay experiments, there will be keen interest in identifying the underlying sources of lepton nonconservation, in characterizing their signatures in other physical processes such as high-energy collisions at the LHC, and in understanding their role in generating the matter-antimatter asymmetry in the early universe through the so-called "leptogenesis" mechanism.

Majorana fermions also appear in solid state physics where they can be associated with electronic quasiparticle states in superconductors. In fact, there is evidence that they have been experimentally observed. The search for a fermion that is its own antiparticle is, thus, an ongoing quest in nuclear, particle, and solid state physics.

Nuclear theory and experiment are also contributing greatly to worldwide efforts to characterize transitions between different neutrino types. One of the most significant discoveries in physics has been the confirmation that neutrinos, the chargeless analogs of the electron, muon, and tauon, oscillate between different types over long distances. These oscillations reveal both the mass differences between different neutrino types and the probabilities for transitions between them. With the effect established, large-scale

experiments in Asia, Europe, and the U.S. are now searching for any differences between the transitions for neutrinos and anti-neutrinos. These charge- and parity- (CP) violating transitions could be responsible for the matter-antimatter asymmetry in the universe. To detect any CP asymmetry, it is critical to correctly characterize the transitions that occur in flight, which requires precise understanding of the interactions that reveal the neutrino's presence in the detector at the end of the journey. Nuclear theory and experiments are contributing greatly to this effort by developing robust experimental and theoretical understanding of the interactions of neutrino and anti-neutrinos with nuclei. Because neutrinos scatter more frequently on neutrons, while anti-neutrinos prefer protons as scattering partners, understanding the difference between neutrino and anti-neutrino scattering requires better understanding of the different dynamics of neutrons and protons in the nucleus. Recent research at JLab, confirmed by neutrino experiments, indicates that the nucleus contains correlated neutron-proton pairs that may skew the nominal velocity distributions of the nucleus and affect neutrino interactions. Ongoing progress in nuclear theory and in experimental measurements of nuclear structure at the 1-GeV scale is having a significant impact on neutrino physics.

Facilities and Institutes—Collaborations Across Disciplines

A wide variety of particle beam and detector capabilities are required to advance the frontiers of nuclear physics. These capabilities are available to researchers at national accelerator user facilities and at university-based facilities. In addition to providing the tools for scientific exploration, these facilities and the associated activities comprise resources that serve the Nation broadly in a variety of ways. Particle accelerator facilities operated for nuclear science research contribute both to meeting the immediate needs of the Nation with their unique capabilities and to the long-term health of the Nation through technology advancements aimed at enhancing capabilities for nuclear science. Nuclear physics facilities are utilized for research in areas that include nuclear security, energy, medicine, climate, the environment, electronics, and forensics. For example, the low-energy facilities that are optimized for research in nuclear structure and nuclear astrophysics provide beams and particle detection systems that are important for nuclear security applications, including nuclear

stockpile stewardship, non-proliferation, and border security. In particular, these facilities play key roles in the programs sponsored by the National Nuclear Security Administration and the Department of Homeland Security to address workforce issues (Chapter 8).

Collaborations and exchanges that engage scientists working in different disciplines contribute to advancing the research frontiers and stimulate new directions of inquiry. Examples of nuclear physics research that significantly overlap with the intellectual interests and technical methods of other fields (e.g., astronomy, astrophysics, cosmology, and particle physics), include nuclear astrophysics, studies of the properties of nuclear matter under extreme conditions of temperature and density, the determination of the properties of neutrinos, and high-precision tests of fundamental symmetries. The overarching missions of the INT and the Joint Institute for Nuclear Astrophysics, Center for the Evolution of the Elements (JINA-CEE) are to create environments that encourage researchers to seek solutions and explore questions beyond the confines of a single discipline and to provide educational opportunities for students and young scientists to work and study in topically rich and multidisciplinary atmospheres. The activities at these institutes, which include workshops, schools, symposia, and visiting scientist programs, are national resources that are important for establishing and maintaining symbiotic interactions between nuclear physics and other disciplines. These institutes provide the nuclear physics community with the nimbleness needed to respond to unanticipated opportunities, particularly those that emerge at the fringes of the field. In addition, they perform key roles in facilitating international collaboration.

10. Budgets

Previous chapters of this Long Range Plan discuss the tremendous recent advances by nuclear scientists in understanding some of today's most compelling scientific questions. Past investments made by the DOE and the NSF over an extended period have yielded world-leading U.S. scientific efforts in the areas of QCD physics, nuclear structure, nuclear astrophysics, fundamental symmetries, and neutrino physics. This Long Range Plan presents the future plans of the nuclear science community in these areas, describing the programmatic evolution required in the next ten years to sustain scientific excellence. This section describes the resources needed to meet these goals.

Federal funding for nuclear physics research is provided by the DOE Office of Nuclear Physics within the Office of Science and by the NSF Nuclear Physics Program within the Physics Division of the Mathematical and Physical Sciences Directorate. The agencies work closely together to maximize the scientific and societal impact of federal spending in nuclear physics, guided by the Long Range Plan recommendations and narrative. The recommendations of the 2007 Long Range Plan were completion of the CEBAF 12-GeV Upgrade, initiation of FRIB construction, development of a targeted program of research in fundamental symmetries and neutrinos, and upgrade of the RHIC luminosity.

Scientific funding can fluctuate from year to year. One large fluctuation occurred in FY 2009 when significant additional funding beyond the base budgets at NSF and DOE was provided through the American Recovery and Reinvestment Act. These funds were primarily devoted to one-time expenditures that accelerated scientific discovery across the field. A second large fluctuation was the budget reduction in FY 2013 (following small reductions of spending power in FY 2011 and FY 2012) that occurred due to the federal budget sequestration. This reduction had the opposite effect, slowing progress within the field. Aside from these two events, one can characterize general trends in NSF and DOE funding. DOE funding from FY 2010 to FY 2015 is shown in Figure 10.1 in FY 2015 dollars along with the FY 2016 President's request (PR). In as-spent dollars, this funding was $535M in FY 2010 and $595.5M in FY 2015, a net increase of about 3.4% above the inflation rate during the period from FY 2010 until FY 2015. The FY 2014

budget restored DOE funding to its pre-sequestration level. Total NSF funding for nuclear physics is shown in Figure 10.2 in FY 2015 dollars. It was $45.8M in FY 2010 and $45.5M in FY 2014 in as-spent dollars, excluding MRIs and mid-scale equipment funding, with the latter competed Directorate-wide. (Final NSF funding distributions in FY 2015 were not available in April 2015.) Taking inflation into account, NSF support for nuclear phyiscs has declined by roughly 10% in real terms in the past five years. This support has increased recently, however, following the decrease due to the FY 2013 sequestration. Another recent change in 2015 at NSF was the transfer of all neutrinoless double beta decay activities from the Particle Astrophysics program to the Nuclear Physics Program, which aligns this science between the two agencies.

Figure 10.1 shows DOE funding separately for Research, Facility Operations, Construction, Projects, and Other. The CEBAF 12-GeV Upgrade project received Critical Decision 3 (CD-3) approval to start construction in September 2008, and FRIB received CD-3 approval to start construction in August 2013. The Total Project Cost (TPC) of the 12-GeV Upgrade is $338M. The FRIB TPC is $730M, of which $635.5M is funded by DOE, with the balance provided by the state of Michigan and Michigan State University. In the period since the 2007 LRP, nuclear physics has undertaken two major construction efforts, whose construction costs total over $1B. The 12-GeV Upgrade will be completed in FY 2017, while FRIB is scheduled to receive CD-4 (project completion) approval in 2022. In order to mount these large facilities, which are investments in the long-term future of the field, the level of support in other areas of the DOE nuclear physics budget has recently been held at constant effort or has declined. This has had an especially significant effect on the level of support for research and for smaller projects and MIEs: research presently accounts for 27.8% of the total DOE budget, down from 31.4% in FY 2010; and there were no MIEs supported by DOE-NP in the first half of FY 2015.

The agencies have also carried out the other major recommendations of the 2007 LRP. The RHIC luminosity upgrade, thanks to technological advances, was achieved at a substantially reduced cost from original estimates. A significant program in fundamental

symmetries and neutrino physics has been initiated, including projects to explore the candidate technologies needed for future ton-scale neutrinoless double beta decay experiments.

DOE Funding in FY 2015 $
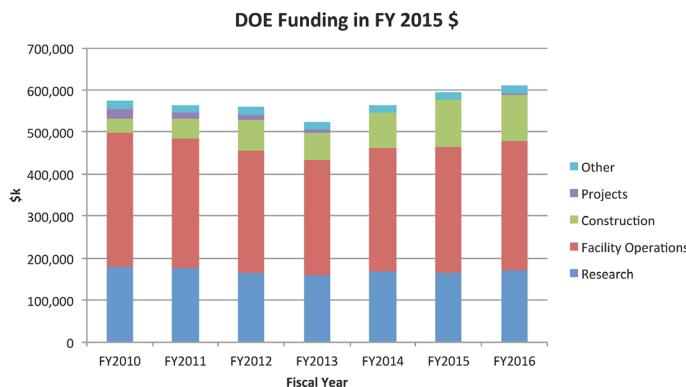
Figure 10.1: *The distribution of DOE nuclear physics funding into different types of activities from FY 2010–2015 (historical data) and for the FY 2016 President's budget request, in FY 2015 dollars.*

A recent review of nuclear physics is the 2013 report of the NSAC Subcommittee on the Implementation of the 2007 Long Range Plan, which provided a mid-term assessment of the nuclear physics program through 2018 in light of funding projections available at the time of that report. This 2015 Long Range Plan provides a new and comprehensive assessment of the nuclear physics program, two years after the 2013 implementation report and with a time window now extending to 2025.

NSF Funding in FY 2015 $
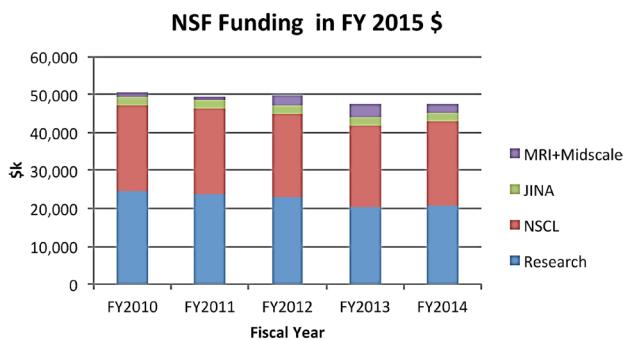
Figure 10.2: *Distribution of NSF nuclear physics funding into different types of activities from FY 2010 to FY 2014 (FY 2015 numbers are not yet available), in FY 2015 dollars.*

CURRENT PROGRAM RESOURCES

The nuclear science program today encompasses research in four related subfields discussed in Chapters 2–5. There are significant intellectual and technological connections between these subfields, and funding boundaries are sometimes diffuse.

Figure 10.3 shows the distributions of major nuclear physics funding activities for the two agencies in different spending categories. DOE funding is separated into operations, research including projects and MIEs, major facilities construction, and other mandated activities. In FY 2015, operations support was provided for three user facilities: ATLAS at ANL, CEBAF at JLab, and RHIC at BNL. The breakdown for NSF is given in terms of research, operations, Physics Frontier Center funding, and MRI and mid-scale funding. NSF operates the Coupled-Cyclotron Facility at NSCL. Effective utilization of NSCL for user operations is needed to keep the U.S. rare isotope community at the international forefront until FRIB construction nears completion. Forward-looking coordination between the NSF and DOE is an essential aspect of managing the successful transition from NSCL to FRIB operations. The FY 2014 budget for NSCL support comprises $22.5M for research and operations of the Coupled-Cyclotron Facility. The agencies also support other low-energy accelerator-based programs at five universities and one national laboratory.

FUTURE PROGRAM RESOURCES

Funding Scenarios

The charge for this LRP requires specification of "what resources and funding levels would be required … to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016–2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025." It is well recognized that resources are always limited, and hard choices must be made for a realistic budget scenario.

The resources required for continuing world leadership in nuclear physics research are provided by a Modest Growth funding scenario, defined as 1.6% real growth per year above Constant Effort. This growth rate is the same as that used in the 2013 NSAC report, *Implementation of the 2007 Long Range Plan*. The budget for the Modest Growth scenario uses the FY 2015 Congressional Appropriation and FY 2016 Presidential Request, with the OMB inflator plus 1.6% real growth per year for FY 2017–2025. The 1.6% rate of increase above Constant Effort is consistent with the multiyear growth

in funding in the FY 2014 and FY 2015 Congressional Appropriations and the FY 2016 President's Budget Request. It also includes the recognition that inflation rates in highly technical scientific enterprises are slightly above the average for the economy. This scenario is not an unconstrained implementation. Careful choices will need to be made between competing science projects, and careful staging of the start of new projects and the completion of others will be required.

FY2015 DOE Budget

FY2014 NSF Budget
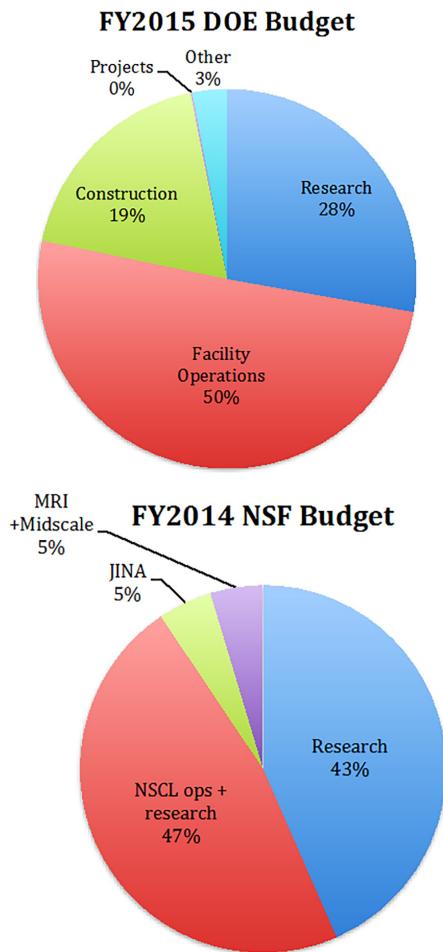
Figure 10.3: *Percentage distribution of budget activities for DOE (FY 2015) and NSF (FY 2014, as FY 2015 was not yet available).*

The impacts and priorities for the Constant Effort scenario are also described below, again with the budget based on the FY 2015 Congressional Appropriation rather than the FY 2015 Presidential Request.

We first discuss the future program under the Modest Growth scenario. We then discuss what additional choices must be made relative to Modest Growth to achieve the Constant funding profile, and what their consequences are.

Modest Growth

In the Modest Growth scenario, all of the major recommendations of this LRP can be accomplished, and a robust science program consistent with the recommendations could be realized.

The first recommendation is to capitalize on investments made by nuclear physics since the 2007 LRP: completion of the CEBAF 12-GeV Upgrade and execution of its forefront scientific program in hadron structure and fundamental symmetries; completion of FRIB and initiation of its scientific program providing world-leading capability for research in nuclear structure and astrophysics; growth and sustained support for the targeted program in fundamental symmetries and neutrinos, including nEDM, other high-profile experiments, and continued R&D leading to the next generation of neutrinoless double beta decay experiments; utilization of the upgraded RHIC facility to explore quark-gluon matter at high temperatures and the spin structure of the proton; and continued operations of the NSCL and ATLAS national user facilities and university-based low-energy facilities. Capitalizing on previous investments also requires healthy research funding levels for university and laboratory researchers.

The second recommendation specifically targets the development and deployment of a ton-scale neutrinoless double beta decay experiment. Demonstration experiments at the scale of 100 kg are currently underway to identify the requirements and candidate technologies for a larger, next-generation experiment, which is needed to be sensitive to postulated new physics. An ongoing NSAC subcommittee is helping to guide the process of the down-select, from several current options to one U.S.-led ton-scale experiment. However, discovery and understanding of this crucial and very rare decay process require that it be measured with more than one isotope; it will, therefore, also be important for U.S. scientists to participate in other experiments, led by scientists in other countries. A program of U.S. leadership in the flagship experiment, participation in complementary experimental efforts that leverage international investments, and enhancement of the theoretical efforts required for the interpretation of these measurements will enable full realization of this unique opportunity to make a fundamental advance in understanding the most basic components of the universe. The down-select process is currently expected

to be completed within three years, at which point the optimum U.S. strategy towards a ton-scale experiment will have been identified. Construction of this flagship experiment is expected to require five years, with capital investment peaking at about $50M/year during this period. This profile increases in the last few years of FRIB construction, when construction funding for that project is decreasing.

The third recommendation calls for initiation of construction of the EIC in the U.S., following completion of FRIB construction. In the Modest Growth scenario, significant investment in EIC construction can be made in the latter years of this LRP time window, as construction of a ton-scale neutrinoless double beta decay experiment is realized and the current scientific mission of RHIC is completed. The EIC will lead to convergence of the current world-leading QCD programs at CEBAF and RHIC into a single facility and represents the future of QCD-related research within the U.S. The EIC will help to keep the U.S. on the cutting edge of nuclear and accelerator science.

The fourth recommendation addresses the need for a balanced portfolio of operations and research at major facilities and in small- and mid-scale projects and initiatives. At NSF there are competitive funding mechanisms that are independent of the nuclear physics base. FRIB begins operations at the midpoint of this LRP, and NSCL transitions from NSF stewardship. NSF will no longer fund operations at Michigan State at that point, and funds previously designated for NSCL operations become available for competition across the entire Division of Physics at NSF. Other chapters in this LRP describe a broad range of outstanding scientific opportunities in nuclear physics, with highly competitive projects that match NSF requirements well. Growing the resources allocated to mid-scale projects will benefit all sciences across the NSF. For the DOE, it is important to maintain a healthy balance between research and facility construction and operations.

Figure 10.4 shows the funding of each major category of the DOE budget as a function of year, in the Modest Growth scenario. The dashed line shows the Modest Growth funding level, while the solid line indicates a constant effort budget. All dollar amounts are shown as $FY 2015. The Modest Growth scenario enables an optimized science program across the four subfields. In this scenario, research support grows continuously

starting in FY 2017, achieving a real increase of $30M/year in FY 2025, consistent with recommendations I and IV. Construction of FRIB ends with Critical Decision 4 approval in FY 2022, and the facility transitions to operations. A ton-scale neutrinoless double beta decay experiment begins construction in FY 2018, and EIC facility construction (beyond R&D and conceptual design) begins in FY 2022, after completion of FRIB and following a period of EIC R&D. Other projects of importance to each subfield are also started and completed in a timely manner in this scenario. A similar modest growth of the NSF nuclear physics budget is assumed to support these projects and research. In order to accomplish all of this in the Modest Growth scenario, total facilities operations funding must decrease in FY 2023, as shown.

This sequence of investments, in which construction of the ton-scale neutrinoless double beta decay experiment begins once FRIB construction funding begins decreasing, and EIC construction begins as construction of the ton-scale experiment nears completion, provides an approximately constant level of investment in new facilities and large experiments that meets the scientific goals of the community in a timely way, while also enabling increased investment in research support, MIEs, and smaller projects. The Modest Growth funding profile thereby enables a balanced future program that builds on the strengths of the current program and investments and establishes new capabilities that will keep the U.S. nuclear physics program at the international forefront for decades to come.

Constant Effort

Under a constant level of effort, a strong nuclear physics program can be maintained, although significant sacrifices will be required in crucial areas. Important program components will be delayed, and some key opportunities will be lost altogether. Research would remain tightly constrained as it was in FY 2013–2014. This will impact the training of highly qualified personnel and may lead to the loss of positions at universities, threatening the pipeline that provides the field and the Nation nuclear scientists, technologies, and ideas. Completion of new experimental equipment at JLab to exploit the science enabled by the 12-GeV Upgrade would be delayed, and new detector systems at RHIC may not be funded. The technology choices for some of the major projects may become more driven by

The 2015 Long Range Plan for Nuclear Science
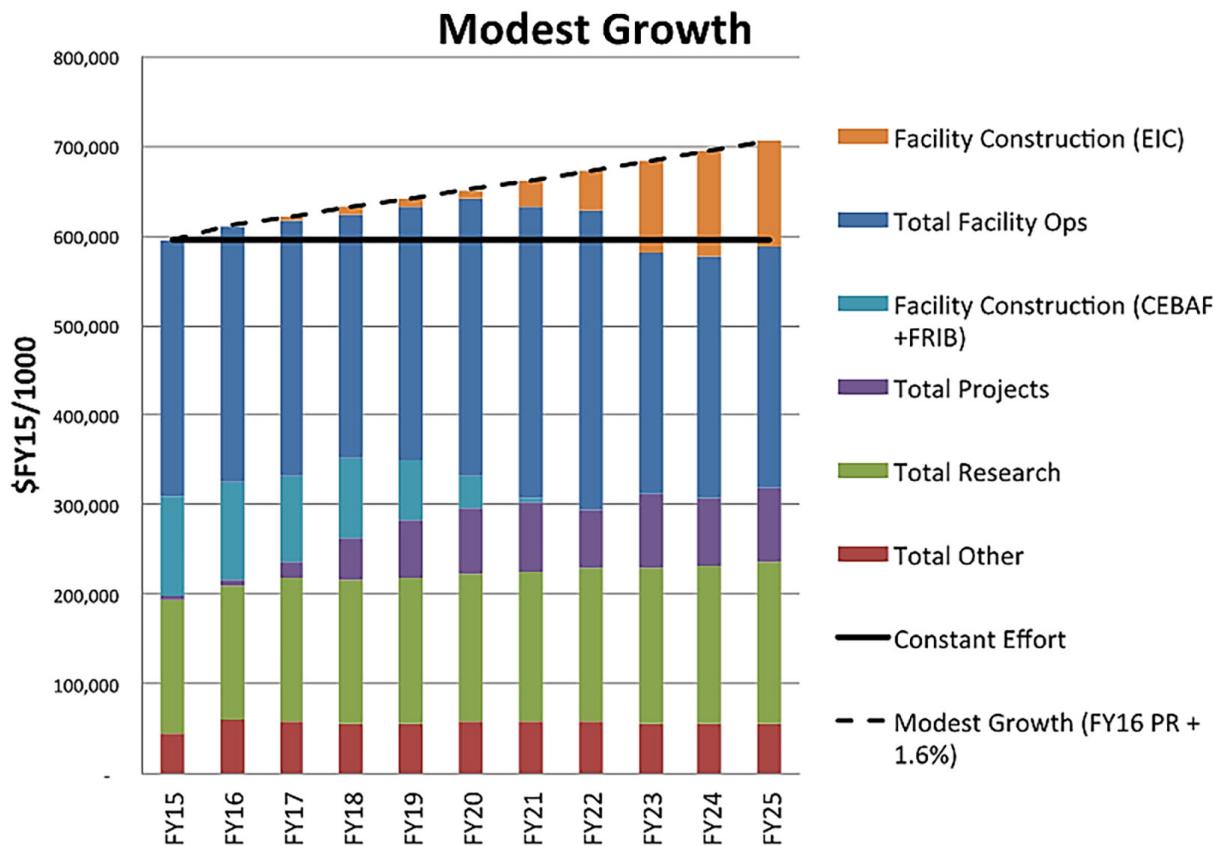
Figure 10.4: *DOE budget in FY 2015 dollars for the Modest Growth scenario.*

cost than by optimizing the science reach. This could affect the international competitiveness of the ton-scale neutrinoless double beta decay experiment and, likely, delay the results. While FRIB facility operations can be maintained, completion of experimental equipment needed to fully utilize FRIB beams would be stretched out in time. Other equipment and facility upgrades will not occur or, at best, will occur more slowly, reducing their scientific productivity.

In the short term, facility operations would need to be reduced from current already constrained levels. A potential, very significant, impact of a constant effort budget is the further reduction in facility operations that would be needed in order to begin EIC construction.

Maintaining the U.S. leadership position in this subfield requires the generation of significant new capabilities for an EIC in a timely fashion. If budgets were restricted to constant effort, proceeding with the EIC as recommended in this plan would be possible only with a drawn-out schedule and would, in addition, require further reductions in funding for operations and research within the QCD program, with adverse consequences for this core component of the overall U.S. nuclear physics

program.

The most difficult choices outlined here for the constant effort budget scenario would occur at or beyond the mid-point of the time window of this LRP. Since nuclear science, like all areas of basic research, evolves in time, it would be unwise to prescribe now what strategy would minimize damage to the field if future budgets dictated such stark choices.

A Forward Look

We have witnessed many major new discoveries in nuclear science over the last decade that were the direct result of the construction and operation of new facilities and detectors as prioritized by previous Long Range Plans. We also have seen a growing use of exciting new technologies developed in nuclear science both in well-established areas of application, such as medicine and isotope production, and in important new areas, such as homeland security. Continuing this growth and reaping the benefits it provides will require new investments. With these investments, the United States will maintain its present world-leading position in nuclear science, and we will continue to contribute to the economic growth, health, and security of our Nation.

Appendix

A.1 Charge Letter

U.S. Department of Energy
and the
National Science Foundation

April 23, 2014

Dr. Donald Geesaman
Chair
DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Dr. Geesaman:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for United States nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the Nation's nuclear science research programs over the next decade. This exercise should exclude the DOE Isotope Program managed by the DOE Office of Science's Office of Nuclear Physics, for which a dedicated strategic planning exercise will be convened.

The new NSAC Long Range Plan (LRP) should articulate the scope and the scientific challenges of nuclear physics today, what progress has been made since the last LRP, and the impacts of these accomplishments both within and outside of the field. It should identify and prioritize the most compelling scientific opportunities for the U.S. program to pursue over the next decade and articulate their scientific impact. A national coordinated strategy for the use of existing and planned capabilities, both domestic and international, and the rationale for new investments should be articulated. To be most helpful, the LRP should indicate what resources and funding levels would be required (including construction of new facilities, mid-scale instrumentation, and Major Items of Equipment) to maintain a world-leadership position in nuclear physics research and what the impacts are and priorities should be if the funding available provides for constant level of effort from the FY 2015 President's Budget Request into the out-years (FY 2016-2025), with constant level of effort defined using the published OMB inflators for FY 2016 through FY 2025. A key element of the new NSAC LRP should be the Program's sustainability under the budget scenarios considered.

The extent, benefits, impacts and opportunities of international coordination and collaborations afforded by current and planned major facilities and experiments in the U.S. and other countries, and of interagency coordination and collaboration in cross-cutting scientific opportunities identified in studies involving different scientific disciplines should be specifically addressed and articulated in the report. The scientific

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impacts of synergies with neighboring research disciplines and further opportunities for mutually beneficial interactions with outside disciplines, should be discussed.
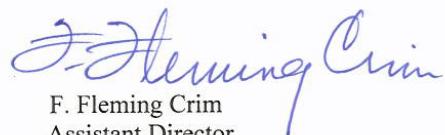
In the development of previous LRP's, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (DNC&T/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again, and to further engage both the DNP/APS and DNC&T/ACS in laying out the broader issues of contributions of nuclear science research to society.

Please submit your report to DOE and NSF by October 2015. The agencies very much appreciate NSAC's willingness to undertake this task. NSAC's previous LRP's have played a critical role in shaping the Nation's nuclear science research effort. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

Patricia M. Dehmer
Acting Director
Office of Science

F. Fleming Crim
Assistant Director
Directorate for Mathematical
and Physical Sciences

A.2 The Long Range Plan Working Group Membership

Ani Aprahamian, Notre Dame University

Robert Atcher, LANL Laboratory

Helen Caines, Yale University

Gordon Cates, University of Virginia

Jolie Cizewski, Rutgers University

Vincenzo Cirigliano, LANL

David Dean, ORNL

Abhay Deshpande, Stony Brook University

Rolf Ent, TJNAF

Renee Fatemi, University of Kentucky

Brad Filippone, California Institute of Technology

George Fuller, University of California-San Diego

Carl Gagliardi, Texas A&M University

Haiyan Gao, Duke University

Donald Geesaman (chair), ANL

Geoff Greene, University of Tennessee

John Hardy, Texas A&M University

Karsten Heeger, Yale University

David Hertzog, University of Washington

Calvin Howell, Duke University

Andrew Hutton, TJNAF

Peter Jacobs, LBNL

Xiangdong Ji, University of Maryland

Reiner Kruecken, TRIUMF

Sebastian Kuhn, Old Dominion University

Krishna Kumar, Stony Brook University

Suzanne Lapi, Washington University, St. Louis

Michael Lisa, Ohio State University

Zheng-tian Lu, ANL

Augusto Macchiavelli, LBNL

Naomi Makins, University of Illinois, Urbana-Champaign

Paul Mantica, Michigan State University

Zein-eddine Meziani, Temple University

Richard Milner, Massachussetts Institute of Technology

Berndt Mueller, BNL

Jamie Nagle, University of Colorado

Witold Nazarewicz, Michigan State University

Filomena Nunes, Michigan State University

Erich Ormand, LLNL

Jorge Piekarewicz, Florida State University

David Radford, ORNL

Krishna Rajagopal, Massachussetts Institute of Technology

Michael Ramsey-Musolf, University of Massachusetts

Hamish Robertson, University of Washington

Thomas Roser, BNL

Patrizia Rossi, TJNAF

Martin Savage, University of Washington

Guy Savard, ANL

Heidi Schellman, Oregon State University

Kate Scholberg, Duke University

Jurgen Schukraft, CERN

Matthew Shepherd, Indiana University

Julia Velkovska, Vanderbilt University

Raju Venugopalan, BNL

Steve Vigdor, Indiana University

Michael Wiescher, Notre Dame University

John Wilkerson, University of North Carolina

William Zajc, Columbia University

International Observers

Angela Bracco, NuPECC

Dong-pil Min, ANPhA

Agency Representatives

Cyrus Baktash, DOE

Frank (Ted) Barnes, DOE

Elizabeth Bartosz, DOE

George Fai, DOE

Manouchehr Farkondeh, DOE

Jehanne Gillo, DOE

Tim Hallman, DOE

Ken Hicks, NSF

Bogdan Mahalia, NSF

Gulsham Rai, DOE

Allena Opper, NSF

James Sowinski, DOE

A.3 Long Range Plan Town Meetings

The four town meetings are

EDUCATION AND INNOVATION IN PREPARATION FOR THE 2015 LONG RANGE PLAN
August 6–8, 2014

Conveners:
Michael Thoennessen (Michigan State University),
Graham Peaslee (Hope College)

Venue: NSCL, Michigan State University

Website: http://meetings.nscl.msu.edu/Education-Innovation-2014

NUCLEAR STRUCTURE & NUCLEAR ASTROPHYSICS MEETING
August 21–23, 2014

Nuclear Structure Conveners:
Mark Riley (Florida State University) and Charlotte Elster (Ohio University)

Nuclear Astrophysics Conveners:
Hendrik Schatz (Michigan State University) and Michael Wiescher (University of Notre Dame)

Venue: Mitchell Institute, Texas A&M University

Website: http://www.lecmeeting.org/

HADRON AND HEAVY ION QCD MEETING
September 13–15, 2014

QCD Heavy Ion Conveners:
Paul Sorensen (Brookhaven National Laboratory) and Ulrich Heinz (Ohio State University)

QCD Hadron Conveners:
Haiyan Gao (Duke University) and Craig Roberts (Argonne National Laboratory)

Venue: Temple University, Howard Gittis Student Center, 1743 N 13th Street, Philadelphia, PA 19122

Website: https://phys.cst.temple.edu/qcd

FUNDAMENTAL SYMMETRIES, NEUTRINOS, NEUTRONS, AND THE RELEVANT NUCLEAR ASTROPHYSICS
September 28–29, 2014

Conveners:
Hamish Robertson (University of Washington),
Michael Ramsey-Musolf (University of Massachusetts)

Venue: Crowne Plaza Hotel near Chicago's O'Hare Airport on 5440 North River Road, Rosemont, IL 60018

Website: http://fsnutown.phy.ornl.gov/fsnuweb/index.html

Other Meetings of Interest

High Performance Computing (Computation in Nuclear Physics), Washington DC, July 14–15, 2014
Authors: A. Burrows, J. Carlson, W. Detmold, R. Edwards, R. Furnstahl, W. Haxton, W. Hix, F. Karsch, W. Nazarewicz, P. Petreczky, D. Richards, M.J. Savage

Website: https://www.jlab.org/conferences/cnp2014/index.html

A.4 Agenda

Agenda
NSAC Long Range Plan Working Group
Resolution Meeting
April 16-20, 2015

Thursday, April 16, 2015

           Open Session
  8:00   Introductory Remarks   Geesaman/Hallman/Opper

  9:00   Science Discussions - Cold QCD (30+20)   Cates
                 Each should present:
                 What has been accomplished since 2007?
                 What can be done over next 5 and 10 years?
                 What major discoveries will emerge?
                 What major new investments are needed?
                     Major facilities
                     Major items of equipment
                     Major focus of research resources
                 Recommendations from Town Meetings
                 Other recommendations for consideration
Note the proposed organization of the report is somewhat different than this science discussion.

  9:50   Hot QCD (30+20)   Nagle
10:40   **Break**
11:00   Fundamental Symmetries and Neutrinos (30+20) Ramsey-Musolf
11:50   **Lunch**
  1:00   Nuclei (30+20)   Nazarewicz
  1:50   Astrophysics (30+20)   Fuller/Wiescher
  2:40   Theory (30+20)   Piekarewicz
  3:30   **Break**
  4:00   Workforce, Education and Outreach (30+20)   Cizewski
  4:50   Broader Impacts and Applications (30+20)   Mantica
  5:40   **Dinner**
                 Closed Session
  8:00   Initial Budget Discussion (30+20)   Jacobs

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Friday, April 17, 2015

National User Facilities:
Each should present:
What are their plans for next 5 and 10 years?
What resources do they need to do this?
Can they deliver the major discoveries discussed on Thursday?

	Open Session	
8:30	RHIC (30+10)	Mueller
9:10	FRIB (30+10)	Glasmacher
9:50	NSCL (30+10)	Sherrill
10:30	**Break**	
10:40	ATLAS (30+10)	Savard
11:20	JLAB (30+10)	Ent
12:00	**Lunch**	
1:30	Electron-Ion Collider (30+20)	Deshpande
2:20	University/Other Laboratory Facilities (30+20)	Wiedenhover

	International Facilities	
3:10	Europe (30+10)	Bracco
3:50	**Break**	
4:10	Asia (30+10)	Ji
4:50	Canada (20+10)	Kruecken
5:20	Underground Science (30+10)	Smith
6:00	SURF (10+5)	Heise
6:15	**Dinner**	

2

Saturday, April 18

                      Open Session
8:30-9:20   Double Beta Decay Scenarios (30+20)   Cirigliano/Wilkerson
                    includes required funding scenarios
9:20   Major upgrades and Major Equipment proposals
                    EDM (15+5)   Filippone
                    GRETA (15+5)   Macchiavelli
                    HRS and other FRIB (15+5)   Zegers
10:20   **Break** [10]
                    JLAB MOELLER+SOLID (15+5)   Kumar
                    SOLID (15+5)   Gao

11:30   Research Portfolio-Experiment [impact of relative research/project funding]
                                        Vigdor
12:30   Research Portfolio-Theory [impact of relative research and computing funding]
                                        Dean
1:30   **Lunch**
                    Closed Session
3:30   First discussion of priorities and recommendations.
5:30   Other issues – Time for discussion of new issues that have emerged.

Sunday, April 19

                    Closed Session
8:30   Continued discussion of recommendations
                    Set overall priorities. Homework assignments for recommendations.
10:45   **Break**
11:00   Status of the report
12:00   **Lunch**
2:00   Discussion of Budgets in light of priorities and recommendations.
3:30   Continue work on recommendations as needed.
4:00   **Break**
4:15   Continue work on recommendations as needed.

Monday, April 20

                    Closed Session
8:30   Finalize language of Recommendations

11:00   Finalize Schedule and Homework assignments, especially for
                    the executive summary, recommendations and resources.

1:00   **End**

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Glossary

A

ALCC	ASCR Leadership Computing Challenge
ALCF	Argonne Leadership Computing Facility
ALICE	A Large Ion Collider Experiment (LHC experiment)
AMS	Accelerator Mass Spectroscopy
ANL	Argonne National Laboratory
ANPhA	Asian Nuclear Physics Association
APS	American Physical Society
ARIEL	Advanced Rare Isotope Laboratory (TRIUMF)
ARUNA	Association for Research at University Nuclear Accelerators
ASCR	Office of Advanced Scientific Computing Research
ATLAS	Argonne Tandem Linac Accelerator System (ANL)
ATLAS	A Toroidal LHC Apparatus (LHC Experiment)
ATTA	Atom Trap Trace Analysis
AdS/CFT	Anti-deSitter Space/Conformal Field Theory

B

BABAR	An e+e- colliding beam experiment at SLAC
BEAMS	Becoming Enthusiastic about Math and Science (JLab)
BELLE II	A future e+e- colliding beam experiment at KEK (Japan)
BES	Beam Energy Scan (RHIC)
BESIII	BEijing Spectrometer III, an e+e- colliding beam experiment in Beijing (China)
BNL	Brookhaven National Laboratory
BOREXINO	A Solar Neutrino Experiment in Gran Sasso (Italy)

C

CARIBU	Californium Rare Ion Breeder Upgrade (ATLAS, ANL)
CBM	Compressed Baryon Matter experiment, an experiment planned at FAIR (Germany)
CD	Critical Decision
CDM	Cold Dark Matter
CEBAF	Continuous Electron Beam Accelerator Facility (JLAB)
CENNS	Coherent Elastic Neutrino Nucleus Scattering experiment (FNAL)
CERN	European Organization for Nuclear Research (Switzerland)
CEU	Conference Experiences for Undergraduates
CGC	Color Glass Condensate
CKM	Cabibbo-Kobayashi-Maskawa
CLAS	CEBAF Large Acceptance Spectrometer (JLab)
CLAS12	CEBAF Large Acceptance Spectrometer for 12 GeV (JLab)
CMB	Cosmic Microwave Background
CMS	Compact Muon Solenoid (LHC Experiment)
CNO cycle	Carbon-Nitrogen-Oxygen cycle of stellar burning
COHERENT	Neutrino Experiment at SNS (ORNL)

COMPASS	Common Muon Proton Apparatus for Structure and Spectroscopy (CERN experiment)
CP	Charge-Parity
CPT	Charge-Parity-Time-Reversal
CPV	Charge-Parity Violating
CRES	Cyclotron Radiation Emission Spectroscopy
CREX	Calcium Neutron Radius Experiment (CEBAF)
CSGF	Computational Science Graduate Fellowships
CUORE	Cryogenic Underground Observatory for Rare Events, double beta decay experiment at Gran Sasso (Italy)

D

DESY	Deutsches Elektronen-Synchrotron (Germany)
DFT	Density Functional Theory
DHS	Department of Homeland Security
DIS	Deep Inelastic Scattering
DNP	Division of Nuclear Physics of the American Physical Society
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DVCS	Deeply Virtual Compton Scattering
DVMP	Deeply Virtual Meson Production

E

EBIS	Electron Beam Ion Source
ECR	Electron Cyclotron Resonance
ECT*	European Center for Theoretical Studies in Nuclear Physics and Related Areas
EDM	Electric Dipole Moment
EFT	Effective Field Theory
EIC	Electron Ion Collider
EMC	European Muon Collaboration
EOS	Equation of State
eRHIC	Electron Relativistic Heavy Ion Collider (BNL Concept of an EIC)
ERL	Energy Recovery Linac
EXO	Enriched Xenon Observatory, double beta decay experiment

F

FAIR	Facility for Antiproton and Ion Research (Germany)
FDG	Fluorodeoxyglucose
FEL	Free Electron Laser
FLOP	Floating point operation
FNAL	Fermi National Accelerator Laboratory
FNPB	Fundamental Neutron Physics Beamline (SNS at ORNL)
FRIB	Facility for Rare Isotope Beams
FSU	Florida State University

G

GANIL	Grand Accelerateur National d'Ions Lourds (France)
GEM	Gas Electron Multiplier
GERDA	Double beta decay experiment at Gran Sasso (Italy)

Glossary

GFMC	Green's Function Monte Carlo
GlueX	Meson Spectroscopy Experiment(JLab)
GPD	Generalized Parton Distributions
GPU	Graphics Processing Unit
GRETA	4π gamma-ray tracking detector
GRETINA	1π gamma-ray tracking detector
GSI	Gesellschaft fuer Schwerionenforschung (Germany)

H

HBCU	Historically Black Colleges and Universities
HDice	A solid polarized hydrogen-deuterium ice target (JLab)
HEP	High Energy Physics
HERA	Hadron-Electron Ring Accelerator (DESY, Germany)
HERMES	DIS experiment at HERA (Germany)
HFIR	High Flux Isotope Reactor (ORNL)
HIAF	High Intensity Heavy Ion Accelerator Facility (China)
HIγS	High Intensity Gamma-ray Source (TUNL)
HMS	High Momentum Spectrometer (CEBAF)
HRS	High-Rigidity Spectrometer (FRIB)

I

ILL	Institut Max von Laue-Langevin (France)
INCITE	Innovative and Novel Computational Impact on Theory and Experiment
INT	Institute for Nuclear Theory (Washington)
ISAC	Isotope Separator and Accelerator (TRIUMF, Canada)
ISOL	Isotope Separation on Line
ISOLDE	Radioactive Beam Facility at CERN

J

J-PARC	Proton Accelerator Research Complex (Japan)
JINA	Joint Institute for Nuclear Astrophysics (Notre Dame)
JIT	Just-in-Time
JLab	Thomas Jefferson National Accelerator Facility, also Jefferson Lab
JUSTIPEN	Japan-U.S. Theory Institute for Physics with Exotic Nuclei

K

KATRIN	Karlsruhe Tritium Neutrino Experiment

L

L1	Level one trigger
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Science Center
LBNL	Lawrence Berkeley National Laboratory
LENA	Laboratory for Experimental Nuclear Astrophysics (TUNL)
LHC	Large Hadron Collider (CERN)
LIGO	Laser Interferometer Gravitational-Wave Observatory
LINAC	Linear Accelerator
LLNL	Lawrence Livermore National Laboratory

LQCD	Lattice QCD
LRP	Long Range Plan
LUX	Large Underground Xenon Dark Matter Experiment

M

MAMI	Mainz Microtron Facility (Germany)
MEIC	Medium Energy Electron Ion Collider (JLab Concept of an EIC)
MEMS	Micro-electromechanical System
MIE	Major Item of Equipment (DOE)
MIT	Massachusetts Institute of Technology
MJD	Majorana Demonstrator Experiment
MOLLER	Parity-violating electron-electron scattering experiment (CEBAF)
MoNA	Modular Neutron Array (NSCL)
MOOC	Massive Online Open Courses
MRI	Magnetic Resonance Imaging
MRI	Major Research Instrumentation (NSF)
MSU	Michigan State University
MSW	Mikheyev-Smirnov-Wolfenstein effect
MUSE	MUon-proton Scattering Experiment at PSI (Switzerland)
Mu2e	Muon to electron experiment (FNAL)

N

NAA	Neutron Activation Analysis
NCSM	No Core Shell Model
nEDM	Neutron Electric Dipole Moment Experiment
NERSC	National Energy Research Scientific Computing Center
NEXT	Neutrino Experiment with a Xenon TPC (Spain)
NIH	National Institute of Health
NIST	National Institute of Standards and Technology
NLDBD	Neutrinoless Double Beta Decay
NLO	Next to Leading Order
NMR	Nuclear Magnetic Resonance
NNDC	National Nuclear Data Center
NNLO	Next to Next to Leading Order
NNSA	National Nuclear Security Administration
NP	DOE Office of Nuclear Physics
NPS	Neutral Particle Spectrometer (JLab)
NRC	Nuclear Regulatory Commission
NRDC	Nuclear Reaction Data Centers Network
NSAC	Nuclear Science Advisory Committee
NSCL	National Superconducting Cyclotron Laboratory (MSU)
NSERC	Canadian National Science and Engineering Research Council
NSF	National Science Foundation
NSSC	Nuclear Science and Security Consortium
NuPECC	Nuclear Physics European Coordinating Committee

O

OLCF	Oak Ridge Leadership Computing Facility
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
OWD	DOE Office of Science Office of Workforce Development

The 2015 Long Range Plan for Nuclear Science

P

PANDA	Antiproton Annihilation at Darmstadt, an experiment planned at FAIR
PDF	Parton Distribution Function
PET	Positron Emission Tomography
PHENIX	Pioneering High Energy Nuclear Interacting Experiment (RHIC)
PIGE	Particle-induced γ-ray Emission
PIXE	Particle-Induced X-ray Emission
PRAD	Proton Radius Experiment (JLab)
PREX	Lead Neutron Radius Experiment (JLab)
PR	President's budget Request
PSI	Paul Scherrer Institut (Switzerland)
PV	Parity-Violating
PVDIS	Parity-Violating Deep Inelastic Scattering
PVES	Parity-Violating Electron Scattering

Q

QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
QGP	Quark-Gluon Plasma

R

RAON	Heavy Ion Accelerator of Korea
RBRC	RIKEN BNL Research Center
RBS	Rutherford Backscattering
RCNP	Research Center for Nuclear Physics (Japan)
ReA3	Reacceleration Linac (NSCL)
REU	Research Experiences for Undergraduates
RESOLUT	In-Flight RIB facility (FSU)
RHIC	Relativistic Heavy Ion Collider
RIB	Radioactive Ion Beam
RIBF	Radioactive Ion Beam Facility (Japan)
RIBSS	Radioactive Ion Beams for Stewardship Science
RIKEN	Institute of Physical and Chemical Research (Japan)

S

SBS	Super Bigbite Spectrometer (JLab)
SCGSR	Science Graduate Student Research Program (OWD)
SciDAC	Scientific Discovery through Advanced Computing
SECAR	Separator for Capture Reactions (FRIB)
SHMS	Super-High Momentum Spectrometer (CEBAF)
SIDIS	Semi-Inclusive Deep Inelastic Scattering
SIS	Heavy Ion Synchrotron at GSI
SLAC	SLAC National Accelerator Laboratory
SM	Standard Model
SNS	Spallation Neutron Source (ORNL)
SNO	Sudbury Neutrino Observatory (Canada)
SNOLAB	Sudbury Underground Laboratory (Canada)
SoLID	Solenoidal Large Intensity Device (JLab)
sPHENIX	Large Acceptance and High Rate Jet Detector (RHIC)
SPES	Selective Production of Exotic Species, an ISOL project at Legnaro (Italy)
SPIRAL	Systeme de Production d'Ions Radioactifs en Ligne, RIB Facility (GANIL)

SPIRAL2	Upgrade of the GANIL Facility
SRF	Superconducting Radio Frequency
SSAA	Stewardship Science Academic Alliance
SSGF	Stewardship Science Graduate Fellowships
SSNR	Summer Schools for Nuclear and Radio Chemistry
STAR	Solenoidal Tracker at RHIC (BNL)
STEM	Science, Technology, Engineering and Mathematics
SULI	Science Undergraduate Laboratory Internships
SuperKamiokande	
	Underground neutrino detector in Japan
SURF	Sanford Underground Research Facility

T

TALENT	Training in Advanced Low Energy Nuclear Theory
TAMU	Texas A&M University
TJNAF	Thomas Jefferson National Accelerator Facility
TMD	Transverse Momentum Distributions
TORUS	Topical Collaboration on the Theory of Reactions with Unstable Isotopes
TPC	Time Projection Chamber
TPC	Total Project Cost
T-REX	Radioactive beam facility at Texas A&M University Cyclotron Laboratory
TRINAT	TRIUMF's Neutral Atom Trap
TRIUMF	Canada's National Laboratory for Particle and Nuclear Physics
TUNL	Triangle Universities Nuclear Laboratory (Duke, NC State, UNC)

U

UCN	UltraCold Neutrons
USQCD	U.S. Lattice QCD consortium

W

WIPP	Waste Isolation Pilot Plant

X

XSEDE	Extreme Science and Engineering Discovery Environment

REACHING FOR THE HORIZON

U.S. Department of Energy • Office of Science • Office of Nuclear Physics
National Science Foundation • Division of Physics • Nuclear Physics Program

October 2015