Report to the
Nuclear Science Advisory Committee

Implementing the 2007 Long Range Plan

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Appendices

Executive Summary

In December 2007, the Nuclear Science Advisory Committee (NSAC) released its most recent Long Range Plan (LRP)—*The Frontiers of Nuclear Science*. The plan contained four recommendations to guide the development of the field over the next decade. To carry them out required investments from the Department of Energy's (DOE) Office of Nuclear Physics (ONP) and the National Science Foundation's (NSF) programs in Nuclear Physics and Particle and Nuclear Astrophysics. Realization of the plan would result in a vibrant program in nuclear science with significant discovery potential and many new applications benefitting U.S. society.

The science of the 2007 LRP was in line with the goal of nuclear scientists around the world, which is to quantify the origin, evolution, and structure of visible matter in the universe. To achieve this requires an understanding of: the strong interaction that governs the structure of nuclei, the structure of the nucleons that form nuclei, and the phase diagram of hot-dense nuclear matter; and the fundamental interactions between particles in the early universe and in stellar environments. Quantum chromodynamics (QCD) is the accepted theory of the strong interaction, but it has proven enormously challenging to apply in practice.

Two U.S. facilities supported by the ONP are used to study the structure of nucleons and the properties of hot-dense matter—the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Over the past decade, both facilities have made forefront discoveries that expand our understanding of strongly interacting systems and QCD. A detailed map of the internal structure of the proton will emerge from current and future work at CEBAF. A new form of matter—a strongly-coupled quark-gluon plasma—has been unveiled using collisions of heavy nuclei at RHIC. Understanding the unique properties of the near-perfect fluid quark-gluon plasma and mapping the phase diagram are the main goals of on-going and future work there.

The U.S. has two user facilities devoted to studying the complex structure of nuclei and determining nuclear properties governing stellar evolution—the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. This area of nuclear science is growing in importance around the world with the development of state-of-the-art rare isotope beam facilities. The accelerators at the U.S. low-energy facilities will be more limited in their capabilities with technology that was developed in the 1970's. The 2007 LRP recommended a major investment be made for this field, the first to occur in many decades for the U.S., with the construction of a next generation rare isotope beam facility.

Many mysteries remain about how our world developed from the big bang. Chief among them is the origin of the excess of matter over antimatter that characterizes the universe today. Nuclear scientists are in the forefront in carrying out experiments that aim to address this question. The answer may lie in an interaction that produces electric-dipole moments in particles. Or it may lie with neutrinos, which have provided many surprising discoveries in the past decade. The 2007 LRP described a suite of experiments that would help resolve these mysteries.

The 2007 LRP was developed during a time when the Administration and Congress had committed to doubling the budgets of the physical sciences over the next decade. Indeed the budgets needed for the investments described in the report fit well within this doubling envelope. To date, significant progress has been made toward attaining the goals of the LRP. But much has changed since 2007—we have been through a global recession and must now cope with growing debt in many economies around the world. With current budget stringencies, NSAC is being asked by DOE and NSF to re-evaluate the priorities for how the field should invest in revitalizing the tools with which nuclear science is done, as set out in the 2007 Long Range Plan. The plan has four major components: (1) complete the upgrade at CEBAF to increase the electron beam energy to 12 GeV and run the program of science that it enables; (2) construct a next generation rare isotope beam facility to vastly extend studies of nuclear structure and nuclear astrophysics; (3) carry out a program of targeted studies in neutrino science and fundamental symmetries; and (4) upgrade RHIC to produce higher beam intensities and upgrade the RHIC detectors to optimize their performance at the higher intensities. The science potential for each of these four components remains extremely high. The projects needed to realize them are being implemented through the ONP and have been proceeding even under budgets that have recently tightened compared to those that were used as a basis for the plan. Losing any one of the components will cause severe and lasting damage to the field. The resources outlined in the 2007 LRP are required to operate an optimized program while following through on the four initiatives. With less support, priorities must be addressed and changes must be made. But those changes depend crucially on the budgets available to the field over the next few years.

Facing potentially devastating budgets, NSAC requested that a report be developed by an NSAC subcommittee to respond to the charge from DOE and NSF of how to implement the 2007 LRP priorities. The letter of April 5, 2012 that describes the charge is attached as an appendix. The subcommittee received substantial input from the nuclear science community while formulating the report. The report provides a forward look at the science capabilities that will follow from investment in each of the four areas put forward in the 2007 LRP. Some of the investments are well underway, others are beginning to occur. The report also discusses the program that can be carried out under several budget scenarios and provides the priorities for how to move forward under these scenarios.

It is difficult to forecast the future impact of a field like nuclear science whose goal is to understand the origin, evolution, and structure of visible matter in the universe. However, history shows that breakthroughs in technology nearly always have come either from science discoveries that "had no apparent application" or from developing the tools that were needed to make the discoveries. Just one of the many examples of this in nuclear science is today's burgeoning accelerator industry for producing particle beams. Particle accelerators have been developed over a period of many decades to explore the structure of nuclei and other subatomic processes. As a consequence of this effort, ion implantation became a standard technique for modifying the properties of solid-state devices and new medical imaging technologies were developed. Today, accelerator construction is a multi-billion dollar industry that serves many sectors of the economy, most notably semi-conductor fabrication and medicine. No one could have predicted this several decades ago.

Under no growth budgets, the question that U.S. nuclear science faces is whether the program should shrink by closing one of its two existing large facilities or by not continuing to construct a new accelerator to produce a state-of-the-art rare isotope beam facility. This stress comes at a time when countries such as China, France, Germany, India, Japan, and South Korea are making large investments in the field. It is clear that leadership will shift away from the U.S. if major cuts are required. Through this report, the subcommittee, with significant community input, gives its assessment of what would be lost under each of these cuts. Under any of the options, the losses would erode the ability to train the next generation U.S. nuclear science work force. This, with the concomitant loss of trained researchers expert in nuclear science, would make our nation poorer and the losses would likely be permanent. Recouping them at a later time would be very difficult, and very expensive. With great reluctance, we give a recommendation that addresses the restrictive flat funding budget scenario. A budget is also presented that while tight would not force a major loss in present or future tools and capabilities. This option adds little to the overall cost of the nuclear science program compared to the value it retains and it is the course that we strongly recommend. Of course funding decisions ultimately rest with Congress. In considering this report, we hope that Congress considers in its assessment the balance between funding for science that is done with a specific short term goal versus the science that seeks to discover new knowledge that may be key to unlocking completely new technology with major long term benefits to society.

I. Introduction

The discipline of nuclear science seeks to explain, at the most fundamental level, the origin, evolution, and structure of the visible matter of the universe. It deals with the simplest forms of matter that are at the same time complex, and as such offers unique opportunities for understanding how the myriad patterns of the world around us emerge from the fundamental laws of nature. While our understanding of the known laws of nature has led to a successful description of a wealth of observed phenomena, basic questions about the visible matter of the universe remain only partially answered. Why does the cosmos contain more visible matter than anti-matter in the first place? How did that matter coalesce into protons, neutrons, and atomic nuclei? How are these building blocks of matter put together and what do they look like from the inside? How is it that a single proton, the hot fluid of quarks and gluons that once filled the universe, and atomic nuclei are all assembled from their constituents with such complexity that they cannot be seen as just the sum of their parts? How do their emergent properties and interactions give rise to the dynamics of strongly interacting matter from the subatomic to astrophysical scales?

The quest to answer these questions inspires young people to begin careers in science, continues to engage some of our nation's brightest minds, and attracts future stars in science and technology from around the world to the U.S. Future investments in capabilities at our national laboratories and universities will give them the tools needed to pursue answers to these questions. The excitement engendered by this enterprise will strengthen our scientific and technical workforce while continuing to spawn technological advances that have far-reaching societal benefits.

Measured by its impact on society, the return on investments made by the U.S. in nuclear science research is large. Nuclear technologies are an integral part of industrial applications and developments. Nuclear science methods provide the foundation on which the most advanced medical diagnostics are built and offer medical treatment of cancer. Nuclear analytics provide the tools for probing rare materials from ancient artifacts to modern space components. Nuclear detector technologies are making airports safer and are protecting our borders. And nuclear energy offers an alternative electrical power source to carbon-based fuels.

Today the scientific challenges of the field are at the forefront of discovery and innovation addressing questions in the quantum physics of complex, strongly-interacting, systems, in the search for symmetry violations that determined the course of the early universe, in the behavior and characteristics of matter at extreme densities and very high temperatures, and in the chemical history and evolution of the universe. The field has evolved from its early years, where the nucleus was studied as an ensemble of neutrons and protons that were held together by what was called the strong force, to one where the nature of that force is being studied by powerful accelerators, which probe the quarks and gluons that form the neutrons and protons. The modern theory describing the strong interaction is called quantum chromodynamics or QCD. For more than two decades, understanding QCD and its role in forming nucleons and complex nuclei has been an important focus of nuclear science research in the U.S., and throughout the world.

The federal government and nuclear science researchers have worked together for more than three decades to chart the course of the field through federal investments. The Nuclear Science Advisory Committee (NSAC) has represented the community in developing a series of Long

Range Plans (LRP) that began with the first plan submitted to the Department of Energy (DOE) and the National Science Foundation (NSF) in the late 1970's. Since NSAC's inception, all major investments in nuclear science have been initiated through the LRP process. Indeed the course of the field has been charted by the major facilities that have been constructed to carry out the cutting-edge science put forward through recommendations from Long Range Plans developed through NSAC.

The most recent LRP was published at the end of 2007. It contained four recommendations for investments for the future U.S. nuclear science program, which are listed here in the order as given in the LRP.

- **We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.**
- **We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.**
- **We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the new Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative**.
- **The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.**

In addition to these recommendations, the LRP looked toward the far future, noting that an "Electron Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier." Recognizing the potential importance of an EIC led to an additional recommendation:

- **We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.**

With support from DOE and NSF, much progress already has been made toward implementing these recommendations. The upgrade of the accelerator complex at Jefferson Lab is approximately 70% complete. Following a competition, the proposal from Michigan State University was selected as the site for the construction of FRIB. With significant contributions from the university and the state, initial site preparation is underway and the group at MSU has demonstrated that they are ready for the Critical Decision 2 review from DOE, which determines the project performance and cost baseline. The accelerator upgrades to obtain the luminosity increase for RHIC II were completed at about one tenth of the initially estimated cost by applying new technology developed at Brookhaven National Laboratory (BNL). The first phase of detector upgrades has been completed at RHIC to utilize the increased luminosity. Progress toward implementing the last part of the third recommendation of the LRP has been negatively impacted due to the cancellation of construction of the Deep Underground Science and Engineering Laboratory by NSF early in 2011. However, the Sanford Lab is operating at the old Homestake Mine location, and a detector for a nuclear physics R&D program is being tested deep underground there. Also, research and development efforts continue on several of the experiments that were highlighted in the LRP as part of the third recommendation. Preliminary studies aimed at developing the technical and scientific case for an EIC have progressed through a cooperative effort endorsed by BNL and Jefferson Lab. There is significant support for the long-term vision of the QCD community to focus their efforts in the U.S. on a single EIC facility.

Despite this progress, the future vitality of the U.S. nuclear science program is at risk. The appropriated FY2012 budget for the Office of Nuclear Physics (ONP) at DOE, which was nearly $60 M below the President's request, fell short of the level that was needed to maintain the momentum to implement the 2007 LRP recommendations. The President's request to Congress for the FY2013 ONP budget was $20M less than the FY2012 enacted budget and the out year projections of flat funding, which would lose ground to inflation over the next five years, would make it impossible to implement the recommendations. This led to a charge to NSAC from DOE and NSF in a letter dated April 5, 2012 stating "We seek advice from NSAC on implementing the priorities and recommendations of the 2007 Long Range Plan in light of projected budgetary constraints and for guidance on developing a plan to implement the highest priority science in the context of likely available funding and world-wide capabilities." The charge specified that at least two budget scenarios should be considered: (1) flat funding at the FY2013 President's request; and (2) modest increases over the next five years. The complete charge letter is appended to the report, as is the charge letter from the chair of NSAC, Dr. Donald Geesaman, setting up a subcommittee to evaluate the science and resources needed to carry it out.

This report from the subcommittee will focus on the science in the field and, in particular, provide a forward look to what science can be carried out under different budget scenarios. Very recently a report from the National Research Council, *Nuclear Physics: Exploring the Heart of Matter*, surveyed the past decade of accomplishments and the future prospects for nuclear science. Four very broad questions were used in that report to frame the field. Those questions serve as an excellent way to introduce modern nuclear science research and are reproduced here.

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

As the knowledge in the field of nuclear science has grown, so has the size and complexity of the facilities that are needed to carry out forefront research in the field. A consequence of this is that fewer facilities exist around the world today than in the past. The U.S. has two major facilities now that are used primarily to study the physics of the strong interaction at the sub-nucleon level—the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Two smaller scale user facilities focus on the physics of nuclei—the Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. All of these facilities have large numbers of users from the U.S. and from abroad. This synergy is important as the users from outside of the U.S. make major contributions to the instrumentation at the facilities thus expanding the science that can be carried out.

Nuclear scientists in the U.S. are also users at major facilities around the world. Recently the scope of investment in new facilities by foreign governments has been large. Since the start of this millennium, well over $5 billion has been spent or will soon be spent on major new nuclear science research facilities in Europe and Asia. This does not include any of the investments made at the Large Hadron Collider. The countries leading the way in this development include China, France, Germany, Japan, and very recently South Korea. A report from the Organization for Economic Co-operation and Development published in 2008 identified the new investments as of late in 2007 and it provided an important context for the further development of new facilities. According to that report
(see http://www.oecd.org/science/scienceandtechnologypolicy/40638321.pdf):

- **planning for the future of Nuclear Physics should be a globally-coherent response to recognized scientific challenges, using an optimal set of national, regional, and, if needed, global-scale projects.**

The development of the major facilities for nuclear science around the world has been following this approach. New investments are being made in facilities outside the U.S. that complement and extend the capabilities now available in the U.S. to study the strong interaction at the sub-nucleon level. Regional facilities are also now being built in other countries with capabilities to produce nuclei very far from stability in quantities that are sufficient to measure their properties. A brief overview of the major facilities used by U.S. nuclear scientists both in the U.S. and abroad is included in this report.

With significant investments being made around the world in nuclear science, the U.S. is in a position of shared leadership in the field. Moreover, as is documented in Section V, a reverse brain drain is underway to countries making significant investments and it could accelerate if the momentum in the U.S. program in nuclear science stalls. From the options and their impacts that are presented in this report, there exists a clear choice for the U.S. If nurtured, the science potential can be realized. And the gains will be of high impact to both our understanding of the world and to making it a better place to live.

II. Nuclear Science – A Forward Look

A. Introduction

Progress in nuclear science research revolves around the interplay between experiments carried out with up-to-date tools and theory that connects the experiments to the underlying physics of the nucleons and their constituents. Research in nuclear science is broad and multifaceted with significant connections among the different parts of the program. Today, these connections extend well beyond our borders and involve interactions with scientists in condensed-matter physics, astronomy and astrophysics, high-energy physics and string theory, cosmology, and atomic, molecular, and optical physics.

The science, its interconnections within the field and with other areas, and its applications have all been reviewed by the National Research Council (NRC2012) in a recent report *Nuclear Physics: Exploring the Heart of Matter*. The overarching questions driving our science are profound. They address the origin and evolution of matter ("How did visible matter come into being and how does it evolve?"), the behavior and properties of strongly-interacting systems ("How does subatomic matter organize itself and what phenomena emerge?"), the nature of fundamental building blocks of the subatomic world ("Are the fundamental interactions that are basic to the structure of matter fully understood?"), and payoffs from basic nuclear science ("How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?").

Nuclear physics contributes in many ways toward meeting the challenge posed by these questions. We live in a universe made of matter, not antimatter. Generating an excess of matter over antimatter requires quantum fluctuations in which quarks can turn into antiquarks or vice versa. Such fluctuations are exceedingly rare today, but they are thought to have been commonplace in the first few picoseconds after the big bang, when the universe was about a thousand times hotter than the quark-gluon liquid produced in heavy ion collisions at RHIC. While the necessity of these fluctuations is theoretically well motivated, there has yet to be any experimental confirmation of their existence.

In and of themselves, however, these quantum fluctuations cannot suffice—there must be some as yet unknown addition to the fundamental forces of nature that "biases the direction" of these fluctuations, favoring the production of matter rather than antimatter. These new forces must violate fundamental symmetries of nature in ways not done by the known laws of nature. If these new forces imposed this bias a few picoseconds after the big bang, they would leave imprints that could be observed today in the neutrons, electrons, and atoms having tiny "electric dipole moments". Another possible symmetry violation that could have biased the quantum fluctuations into making visible matter even earlier in cosmic history would be evident today through very rare radioactive decays of heavy nuclei in which two electrons but no neutrinos emerge. The result of this interplay of quantum fluctuations and symmetry violations was a soup, or "plasma", of quarks and gluons that existed microseconds after the big bang, out of which protons and neutrons—the building blocks of matter—emerged.

The process in which protons and neutrons coalesced out of the quark-gluon plasma is called hadronization. The physics of hadronization and the physics that governs the internal structure of the nucleons are contained in quantum chromodynamics, the theory of interacting quarks and gluons, but the mechanism of hadronization is exceedingly difficult to understand. One way that this problem is being attacked is by constraining calculations that can be done today with precision measurements probing the internal structure of the nucleon. Many surprising discoveries have come out of such measurements. One of the most puzzling has been the discovery of the complex nature of the proton's spin. Throughout much of the twentieth century, the nucleon spin was viewed as an intrinsic property, just as the electron's spin is viewed today. But we now know that there is very complex physics that leads to the simple nucleon spin of one-half.

The nucleons that condensed out of the primordial soup of quarks and gluons soon began interacting in the early universe producing the first complex nuclei. After billions of years of processing, the full range of elements now found on earth was produced. This nucleosynthesis process continues today in stellar systems throughout the universe. Much has been discovered about the pathways of nucleosynthesis, but there are still many missing links. Among the most important pathways is the one that leads to the heaviest elements found on earth. Neither uranium nor thorium can be produced in stars by a simple process starting from the heaviest stable nuclei, lead and bismuth. The path must involve a succession of very rapid neutron capture reactions, which produce many isotopes that have not been observed on Earth. We now know that detailed knowledge about these short-lived isotopes cooked in stellar events is essential for understanding how neutrons and protons are assembled into nuclei found in nature. Producing and studying these very neutron-rich isotopes, which also have significant practical applications, is one of the key goals of twenty-first century nuclear science.

The future science program described in the remainder of this section begins with the two sections that directly confront QCD—the physics of hadrons and the science of the quark-gluon plasma. This is followed by the physics of nuclei, nuclear reactions, and nuclear astrophysics, and a discussion of nuclear-science work on fundamental symmetries and neutrinos. The last part of the section discusses how nuclear theory interacts with, links, and guides all of these areas. As stated above, an excellent review of the accomplishments of nuclear science over the past decade is contained in the recent NRC2012 report. Rather than repeat what is already chronicled there, the subcommittee has chosen to focus on future opportunities for the field.

B. Hadronic Physics

Introduction

In the Standard Model, the strong, weak, and electromagnetic interactions are unified into a theory that describes our present understanding of the universe. Much of the nature of the visible matter in the universe is determined by the part of the Standard Model known as quantum chromodynamics, or QCD. QCD describes the interactions among its fundamental constituents—quarks and gluons—as they exist in composite particles, known as hadrons, the quark-gluon plasma, and inside nuclei. Confinement, a fundamental property of QCD, dictates that quarks and gluons normally exist only inside composite particles, making it impossible to study them in isolation. Rather they must be viewed using powerful microscopes that can probe the interiors of hadrons and nuclei. Quarks were first introduced to explain particles such as the nucleon as a bound state of three quarks, called valence quarks. While this simple model describes some of the properties of hadrons, it provides little insight into fundamental properties like their masses and intrinsic spins. QCD has provided the framework to understand these properties, and much more. For example, QCD tells us that the proton mass is dynamically generated by an intense field of gluons that interact amongst themselves and with the quarks. In fact, the gluons of QCD are directly responsible for generating 99% of the mass of the nucleon and hence that of the visible universe. The gluons also give rise to the force between nucleons—a delicate balance of attractive and repulsive interactions—that is responsible for building the cores of all the elements in the periodic table.

Understanding the internal structure of protons and neutrons is one of the essential ingredients in developing a more comprehensive picture of nucleons and nuclei. Nuclear scientists must use powerful experimental probes to reveal this complicated structure of quarks, gluons, and quark-antiquark pairs, also known as the "sea" quarks. Among the sea-quarks are pairs of strange and anti-strange quarks. For many years, nuclear theorists thought that strange quarks were important in determining some key properties of the proton. Measurements of parity-violation (violation of mirror or reflection symmetry) in electron scattering experiments in laboratories in the U.S. and Germany have provided a direct look at the strange quarks in the nucleon and determined that their role in defining the proton structure is limited. It is the valence quarks, gluons, and sea-quark pairs from the lightest quarks—the up and down quarks that also are the valence quarks in the neutron and proton—that mostly produce the rich internal structure of the nucleon. This has opened the door to measurements that can differentiate between the up and down quark distributions in the proton. The 12 GeV CEBAF Upgrade, together with its new instrumentation, will take this effort to a new level, providing unprecedented new opportunities. These advances will also allow nuclear scientists to study excitations of the gluon field and to produce new tomographic images of the interior of the nucleon, revealing in greater detail than ever before the underlying quark-gluon dynamics. The results to come from the new experiments at the 12 GeV CEBAF Upgrade will provide a major step forward towards the goal of being able to describe and understand the structure and properties of nuclei from QCD.

The research to be carried out using the 12 GeV CEBAF Upgrade is a key part of the effort to address the nature of QCD that is responsible for the properties of hadronic (i.e., strongly interacting) particles. A coordinated program of experiments is planned for this new facility that will greatly expand the boundaries of our understanding of QCD in this regime. When these are combined with the robust theory and computational efforts currently underway, we will be able to address some of the most important questions facing nuclear physicists today. One such question is posed by the important discovery made two decades ago that the spins of the quarks inside a proton account in sum for only about a quarter of the total proton spin, meaning that our understanding of how the constituents of a proton fit together in QCD is far from complete.

The RHIC-Spin program will make unique and complementary contributions to resolving this puzzle, with measurements there and at the upgraded CEBAF together advancing the understanding of how the motions of the quarks (measured at CEBAF) and the spins of the gluons (measured at RHIC) within a proton contribute to its spin.

Research into the nature of hadrons and confinement has a broader international context through the ongoing COMPASS experiment at CERN and new programs envisioned at hadron-beam facilities such as the Japan Proton Accelerator Research Complex (J-PARC), and the future Facility for Antiproton and Ion Research (FAIR) at the existing Gesellschaft für Schwerionenforschung (GSI) facility in Germany.

Below, four questions are used to highlight both the recent progress in the field and what will be gained with the 12-GeV Jefferson Lab as the centerpiece of the future program.

What is the nature of gluon fields in protons that make up 99% of the mass of the visible universe?

While QCD in its low-energy domain describes the protons and neutrons in the visible universe, this domain is also where the complexities of QCD can give rise to dramatic phenomena. Perhaps the most striking property is also the least well understood—the confinement of quarks and gluons inside protons. Unlike atomic physics, where excitation will eventually produce free electrons (i.e., ionization), the excited hadrons of QCD *never* emit free quarks or gluons. Recent lattice QCD calculations, utilizing leadership-class supercomputers, have for the first time produced detailed predictions for the existence of new particles that are associated with excitations of the gluonic field inside bound quark-antiquark systems known as mesons. Investigations of the systematic properties of these excited particles, and in particular those due to excitations of the gluonic field, will provide much needed information about the mechanisms that are believed to be responsible for confinement in QCD.

Producing these new particles, measuring their properties, and comparing these measurements with the improved predictions from theory will provide an important window on the properties of low-energy QCD. High-energy electron and photon beams, such as those generated at Jefferson Lab, can probe and excite the confined quarks and gluons to reveal the dynamics associated with them. These tools will allow us to study the production mechanisms of these new particles, and if they are produced their study will be a central part of the 12 GeV CEBAF Upgrade program. While the lattice calculations already hint at interesting properties of these excited gluon fields, the detailed program of experiments at the upgraded facility is necessary to establish their existence and explore their properties.

These future experiments have been provided with a strong theory foundation, by significant advances in the ability both to predict the masses of the excited exotic hadrons of QCD and to understand the nature of the excitations themselves. In particular, in the case of meson states (quark-antiquark systems), the predictions provide a means to identify which excited states are associated with an excitation of the gluon field as opposed to being just excitations of the quarks and antiquarks. Figure II-1 illustrates the pattern of these gluonic excitations. What is most striking about these predictions is that they show excited states that could not exist if there were no excitations of the gluon field. The experimental observations of these so-called "exotic hybrid mesons" would provide crucial verification of recent lattice QCD calculations of their masses, and would launch a new effort to study the properties of gluonic excitations and their relation to confinement in QCD.

A key part of the 12-GeV physics program at Jefferson Lab is the ability to produce these exotic hybrid mesons using photon beams, which is expected to generate unprecedented numbers of these particles. The GlueX experiment in the new Hall-D is poised to carry out this program using a detector designed to tackle just this problem. The GlueX experimental program is coupled with both detailed lattice QCD predictions and the strong support of the Jefferson Lab theory center in analyzing and interpreting the expected new data. This puts the U.S. in a unique position to explore this important new science made possible by the 12 GeV CEBAF Upgrade. During its first few years of running, GlueX will search for and study the spectrum of excited gluonic states. If evidence for exotic hybrid mesons is found in these studies, further, high-intensity running will make it possible to elucidate the properties of the gluonic excitation and improve our understanding of QCD, in particular the mechanism for confinement.

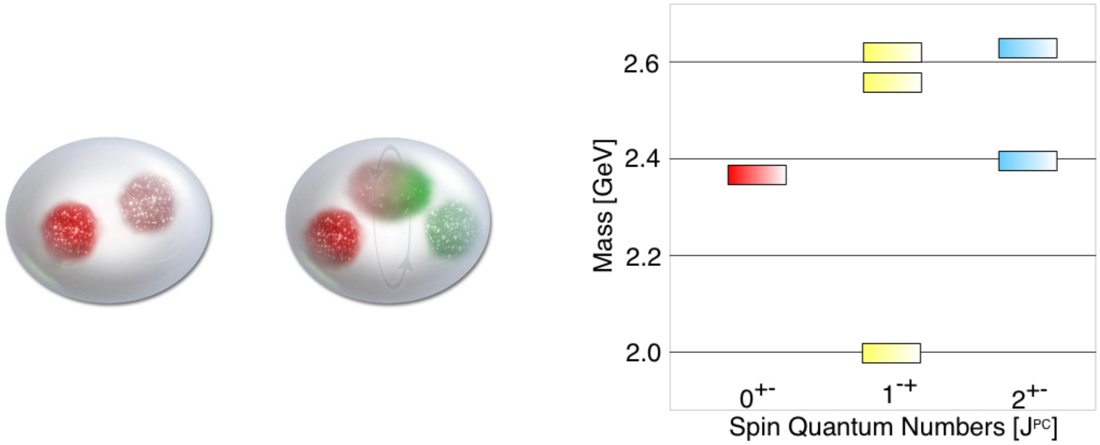


Figure II-1. The left-hand image shows a particle formed by a quark and an antiquark. Recent lattice QCD predictions indicate that the gluon field that binds the system can be excited (as shown in the middle image). These calculations also predict additional particles resulting from gluonic excitations in QCD (right-hand image). Mapping the pattern of these states in experiments at the 12 GeV CEBAF Upgrade will allow us to study the excited gluonic field of QCD. The right-hand image shows the predicted patterns of these new particles related to the excitations of the gluonic fields; the colors represent the different spin quantum numbers predicted by lattice QCD.

What do new multi-dimensional spatial and motional pictures of the proton reveal?

Over the last decade, there have been major advances in the understanding of the distribution of quarks inside the proton. Much of this has been driven by technological breakthroughs and the experimental program centered at Jefferson Lab. Recent results have for the first time revealed the difference between the distributions of up- and down-type quark charge in the proton. This work has also inspired major advances in our theoretical understanding of these distributions. Instead of simple one-dimensional distributions, they are now formulated and measured via more comprehensive three-dimensional distributions of the quarks and gluons in the proton. An extensive experimental program planned at the 12 GeV CEBAF Upgrade will greatly expand the information needed to determine this internal three-dimensional landscape of the proton, and more importantly it will enable the use of the distributions to address important outstanding questions on the structure of the proton quantitatively.

A detailed investigation of the structure of the nucleon is essential for a fundamental understanding of the properties of the nucleon, and those of all known nuclei, based on QCD. This is a challenging task because of the complexity associated with strongly interacting, many-body systems—the nucleon itself is a many-body problem, and a nucleus is still another many-body system. Despite this complexity, in the last ten years we have entered a new era where a framework suitable for a comprehensive and quantitative approach to the description of nucleon structure based on QCD has emerged.

In classical mechanics, a complete description of the structure of a complex object can be achieved by specifying how many of its constituent particles have given values of the three position coordinates and three momentum coordinates. In 1932, Wigner introduced the appropriate quantum mechanical generalization, namely a six-dimensional distribution function that respects the fact that in quantum mechanics the position and momentum of a particle cannot both be known with certainty. Two sets of three-dimensional structure functions of the nucleon can be derived from the Wigner distributions, which provide new information about the structure of the nucleon. They are the Generalized Parton Distributions (GPDs) and Transverse Momentum-dependent Distributions (TMDs).

The GPDs provide a route to spatial tomography of the nucleon and have revolutionized how we characterize nucleon structure, by allowing a unified description of the quark densities in spatial coordinates in relation to their momenta. This combined description for the first time includes the correlations between the position and momentum of the quarks. As a direct consequence of this correlation, GPDs provide a new way to characterize the contribution of the orbital motion of quarks to the spin of the proton. (This is an important related subject, discussed further in the next section.) Accessing these GPDs requires a dedicated effort utilizing specialized experimental apparatus, and is the focus of a sizable part of the program of the 12 GeV CEBAF Upgrade.

The TMDs are obtained from the same Wigner distributions, but are expressed only in terms of momentum. They hold information about the quark/gluon intrinsic motion in a proton (or a neutron), and the relation of the quark momenta with the spin of either the proton or of the quark. Such correlations between spin and motion are similar to those found in other fields of physics, such as in excited states of the hydrogen atom and in topological insulators. Most TMDs are expected to vanish in the absence of quark orbital motion; as such, measurement of nonzero TMDs will provide important and complementary ways to access the contribution of this to the spin of the proton. TMDs can be measured in experiments using electron or muon beams, and proton or pion beams, and each has an interesting story to tell. For example, imagine the following: a quark inside the proton is given a kick in a certain direction, and the proton is spin-aligned perpendicular to the direction of the kick. The TMD in this process then probes the correlation between the proton's spin and the orbital motion of the quark. This correlation can be observed as a left-right preference in the distribution of the outgoing hadron formed from the quark.

Experiments utilizing the 12-GeV beam and high-performance spin-polarized targets at the upgraded CEBAF will allow for a precise determination of these important functions and enable a high-resolution imaging of the nucleon in three-dimensional momentum space. The aforementioned example is illustrated in Fig. II-2. In such distributions, a non-zero value requires orbital motion of the quarks. As a direct consequence, the orbital motion of the valence quarks within a proton will be measured at Jefferson Lab in the 12 GeV era.

The experimental access to GPDs and TMDs was pioneered in the last decade in laboratories in Japan, Germany, Switzerland and the U.S., motivating substantial theoretical development that has now established a framework for the more definitive studies to come. These studies will be continued at CERN by the COMPASS collaboration and will also be explored at RHIC. The 12 GeV CEBAF Upgrade, with high luminosities, high polarizations, and new instrumentation, offers the unique tools needed to unravel the three-dimensional structure of the nucleon in the valence quark region.

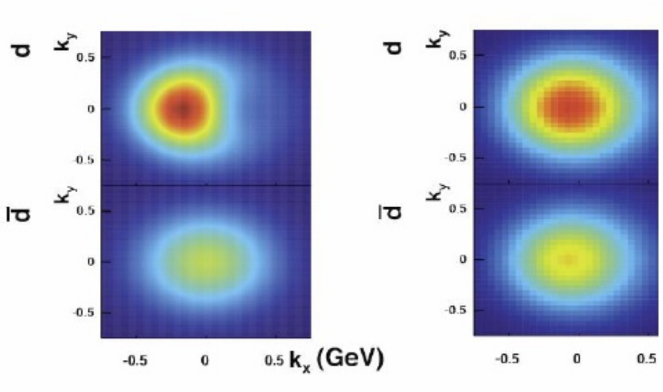


Figure II-2. The down quark and anti-down quark momentum distributions in the example TMD mentioned above at a momentum fraction of 0.1 for the momentum kick of the quark (antiquark) relative to the total momentum kick of the parent proton. Presently available data on these momentum distributions (right panel) do not have the resolution to reveal any interesting structure while the simulations (left panel) show that data from the 12 GeV CEBAF Upgrade will have the resolution needed to make a possible dipole deformation clearly visible.

How is the spin of the proton assembled from the spins and motions of all of its parts?

Spin is a fundamental property of all elementary particles and atomic nuclei. While the spin of such tiny objects is, loosely speaking, similar to more familiar phenomena such as the spin of toy tops and the rotation of planets, quantum mechanics has an essential influence over the spin of particles and nuclei, making its behavior quite different from spin effects of macroscopic objects in our everyday world. Practical application of the spin of particles and nuclei can be found in the petroleum industry, chemistry, medical imaging, and in quantum computing, and physicists continue to discover new phenomena and applications involving spin. One important example is spin transport electronics, an emergent technology in which both the electron's spin and magnetic moment are used in solid-state devices. A more recent discovery involving spin is a new type of material called a topological insulator, which behaves like an insulator in its interior but like a conductor on its surface, due to an intricate interplay between the spins of the electrons in the material and their motion.

Our knowledge about the spin of the proton, the fundamental building block of visible matter, has major holes. Protons are spin-1/2 particles. Physicists thought for quite some time that this spin arises simply and directly by adding up the spins of all the quarks inside the proton. In the late 1980s, it was discovered that all the quark spins in sum contribute only about 25% of the total proton spin. Detailed polarization experiments worldwide carried out over the last two decades have confirmed this result. The rest of the proton's spin can only come from the gluons and from the orbital motion of the quarks. The unique polarized proton capability at RHIC has been used to explore gluon contributions to the proton's spin. Very recent results from the RHIC-Spin program have provided the first indication that the spin of the gluons contributes to the spin of the proton. Measurements to come at RHIC will significantly improve the precision of this determination as well as clarifying the role of the spin of antiquarks. However, there are already strong indications that these contributions alone do not suffice, and there is likely to be a further contribution from the orbital motion of quarks and gluons, which is essentially unexplored as of now. The discovery that a proton, in its ground state, contains quarks and gluons whizzing around with nonzero angular momentum would be striking and important. This would make the proton fundamentally different from, say, a hydrogen atom in its ground state. A very interesting question to ask is, how is the orbital motion shared between gluons and quarks?

Figure II-3. Both the proton and its constituent quarks have spin. An old picture of the proton spin (left) in which the spin of the proton was thought to arise from the contribution of the intrinsic spin of quarks has been known for quite some time to be incorrect. A more complicated picture of the proton spin is presented (right), in which the orbital motion of the quarks and gluons is expected to contribute to the proton spin (see text).

The description of orbital motion of quarks and gluons has remained elusive until recent theoretical and experimental breakthroughs in the GPD and TMD formalisms discussed in the previous section. Preliminary constraints on the orbital motion of the *u* and *d* quarks have become available from first sets of experiments carried out by the HERMES collaboration at DESY in Germany, the COMPASS collaboration at CERN, and the 6-GeV program at Jefferson Lab. With the 12 GeV CEBAF Upgrade and new instrumentation, the contribution to the spin of the nucleon made by the orbital motion of valence quarks will be measured, as we have described in the previous section. The spin program from COMPASS-II at CERN will complement the 12-GeV spin program at Jefferson Lab by probing the sea quarks and will help to address the question of the contribution of the orbital motion of the sea quarks to the spin of the proton.

Further, measurements at RHIC utilizing a weak interaction process have been demonstrated to be a novel and a clean probe with which to access the contribution of the proton spin from the sea quarks and antiquarks. New data from the RHIC-spin program will provide precise information about this important contribution. In addition to providing a decisive elucidation of the extent to which antiquarks play a role in the proton's spin, the measurements will show whether anti-up and anti-down, the two lightest antiquarks, carry similar polarization. Plans are also in place to access TMDs using a process in which a quark annihilates with an antiquark at RHIC. This will show correlations between the proton's spin and the orbital motion of quarks at smaller transverse length scales than those studied at JLab, providing important complementarity. The unprecedented flexibility of the RHIC collider will also provide a unique opportunity to compare how neutrons and protons are put together using high-energy collisions between polarized protons and polarized helium-3, complementary to measurements at longer length scales employing polarized helium-3 targets at Jefferson Lab. In summary, concerted efforts spanning several labs will write a new chapter in the book of the proton spin.

How do nuclei emerge from QCD?

The deuteron is the simplest nucleus, consisting of one proton and one neutron. The nuclear force that binds the proton and neutron into a deuteron becomes repulsive at short distances when the proton and neutron come very close to each other. This short-range repulsive behavior is a basic component of all nuclei, required to prevent catastrophic collapse. Thus, the delicate interplay between attraction and repulsion that enables the existence of atomic nuclei, and therefore chemical elements, is a vital topic for current research. Probing the short-range correlation between a pair of nucleons by knocking out the pair using an electron beam, as illustrated in Fig. II-4, helps to elucidate the nature of short-range repulsion in the nucleon-nucleon force.

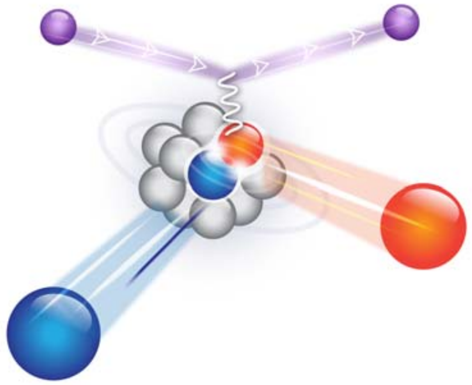


Figure II-4: The knock out of a proton-neutron pair from a nucleus shown as blue and red balls by a powerful electron beam shown as purple for both the incoming and outgoing electron.

Nuclear scientists learned more than two decades ago that the environment inside nuclei modifies the behavior of quarks and gluons compared to their properties inside a single proton or neutron alone. Understanding how that same nuclear environment is shaped by the interactions of quarks and gluons is an important goal of the field. Experiments made possible by the 12 GeV CEBAF Upgrade will provide new clues by probing the very short-range forces between nucleons inside nuclei. At the same time, a state-of-the-art parity-violating electron scattering technique has also emerged as a powerful way to measure the thickness of the "skin" of neutrons outside the dense cores of heavy nuclei, a feature that can be related to the pressure of neutron matter. This effect is important for our ability to estimate the size of neutron stars.

What for many years was called the nuclear force is now known to result from a delicate balancing of QCD interactions. Lattice QCD describes how quarks and gluons form protons and neutrons, but how does this complex interaction manifest itself in yielding nuclei? It appears that the quark-gluon structure of protons and neutrons bound in nuclei is modified when compared to the properties of free nucleons. The 12 GeV CEBAF Upgrade program will use the nucleus as a laboratory to explore QCD and study the QCD structure of nuclei. It will be possible to confirm that the modification of nucleon properties in nuclei is related to the local or short-distance nuclear environment, and to study how this varies as the amount of binding changes. It is also well known that there exist short-distance correlations between protons and neutrons in nuclei, resulting in local pairs of nucleons. Recent results indicate that there are many more high-relative-momentum proton-neutron pairs than other pairs, and there is a relation between these proton-neutron pairs and the modified quark-gluon structure of the nucleons in nuclei. Experiments can quantify this relationship and illustrate how the modification is related to the short-distance repulsive nature of the nuclear force.

Advances in recent years in lattice QCD show great promise toward direct calculation of the properties of the nuclei of the lightest elements. However, the ability to directly calculate the nucleon-nucleon force still has a very high computational cost and will remain a tremendous challenge for theory for some time. Current calculations of even the most basic quantities characterizing the nucleon-nucleon interaction require unphysical simplifying assumptions, given the limitations of currently available computer power, and so their results are far from experiment. After many decades of study, the basic mystery of the origin of nuclei still remains. Seeing how nuclei emerge from QCD and understanding their properties and structures from QCD are an important part of the nuclear physics program. Experimental data from the 12 GeV CEBAF Upgrade on details of the nucleon-nucleon interaction at short and medium distances will be crucial to realizing this goal.

Parity-violation measurements offer another way to probe the short-distance behavior of the nuclear force and its relation to QCD. As with studies of the strange sea-quarks, the use of parity-violation in scattering of electrons from heavy nuclei, and parity-violating scattering between light nuclei themselves, can reveal manifestations of fundamental quark-quark interactions in nuclei that would otherwise remain obscured from view. In particular, parity-violating effects in the scattering of light nuclei is sensitive to the weak force between quarks, whose implications for nuclei have been studied for decades but remain poorly understood. Recent advances in techniques for measuring these effects, coupled with progress in effective field theory and lattice QCD, promise a new era of insight into this long-standing problem. The most sensitive such measurement to date comes from studying the capture of a neutron by a proton which then turns into a deuterium nucleus and radiates a photon. The experiment studying this is collecting data at the Spallation Neutron Source located at the Oak Ridge National Laboratory and new measurements have been proposed for that facility. An experiment to investigate the inverse process is being discussed for the High Intensity Gamma Source at the Triangle Universities Nuclear Laboratory (TUNL) if an upgrade to higher flux is carried out.

Yet another use of parity-violating electron scattering was recently demonstrated through a unique set of experiments to measure the thickness of the neutron skin in heavy nuclei (see Section IID). The thickness of the neutron skin is directly related to how nuclear binding changes with density when neutron and proton density distributions differ. Knowing this density dependence constrains models of finite nuclei and also informs us about the properties of dense astrophysical objects. In particular, the neutron skin thickness in heavy nuclei can be related to the pressure of neutron matter, at a given density, and it is this pressure that supports neutron stars against gravity. Indeed, theoretical calculations suggest a strong correlation between the neutron skin thickness of a heavy nucleus and neutron star properties such as radius, crust-to-core transition density and even the fraction of protons in the interior of the star.

The atomic nucleus provides a laboratory that can complement our studies of uniquely QCD phenomena, namely how a strong gluonic field is converted into hadrons. By using the electron beam available at Jefferson Lab to strike a single bound quark in a bound proton, we can observe both how the struck quark interacts with the rest of the struck proton and how the quark forms into the colorless bound states of QCD as it emerges from the nuclear medium.

Summary

The 12 GeV CEBAF Upgrade when completed will transform Jefferson Lab into a remarkable facility that will provide a number of outstanding opportunities to understand the nature of QCD, the nucleon, and the nucleus. In addition, the unprecedented combination of high intensity, high energy, high longitudinal polarization and beam stability yields unique capabilities that make possible a new generation of experiments probing the nature of fundamental forces in the very early universe. These initiatives, which are described in more detail in the section on Fundamental Symmetries and Neutrinos, propose to make ultra-precise measurements of parity-violation in electron scattering and new searches for "dark photons" that might be associated with dark matter.

The research carried out at Jefferson Lab is complemented by ongoing experimental programs to study the role of gluons and sea quarks in the proton at RHIC and by other international efforts. The U.S. initiatives are seen as integral and crucial components of a worldwide effort. There is a large and active international community studying QCD, confinement, and precision tests of the Standard Model; Jefferson Lab is clearly providing the U.S. nuclear physics program with a world leadership role. With the successful upgrade, Jefferson Lab will be a flagship for this diverse scientific program for many years to come.

C. The Science of Quark-Gluon Plasma

A look backwards in time reveals a universe at higher and higher temperatures. Just a microsecond after the big bang, the entire universe was millions of times hotter than the center of the sun. As the infant universe cooled, it passed through various phase transitions, just as steam condenses to water and then freezes to ice. Above some almost unimaginably high temperature, it is possible that all known forces of nature were unified. A few microseconds after the big bang, the forces of nature were as we know them today but, because the universe was many trillions of degrees hot, the matter that filled it was still unrecognizable: no protons or neutrons had yet formed, therefore no nuclei, no atoms, and no molecules. The entire universe existed as a primordial fluid of quarks and gluons, called quark-gluon plasma, until after about 20 microseconds it "condensed", forming protons and neutrons, the first complex structures in the universe.

The most powerful accelerators in the world today are capable of colliding nuclei at such high energies that they can recreate droplets of the quark-gluon plasma that filled the microseconds-old universe, making it possible to study its properties in the laboratory and answer questions about the nature of the new-born universe that will never be accessible via astronomical observation. The formation of protons and neutrons from quark-gluon plasma is likely to be the earliest scene in the history of the universe that will ever be re-enacted in the laboratory. Each nuclear collision at RHIC makes a droplet of quark-gluon plasma, exploding in a "little bang" which recreates the transition by which the first protons and neutrons were formed. These experiments allow us to see the essence of the fundamental nuclear force, as described via the theory of QCD. Although the analysis of the experiments is challenging due to the short lifetime and small size of these droplets, we have the advantage of billions of little bangs to study as well as a surprising degree of control over their initial conditions.

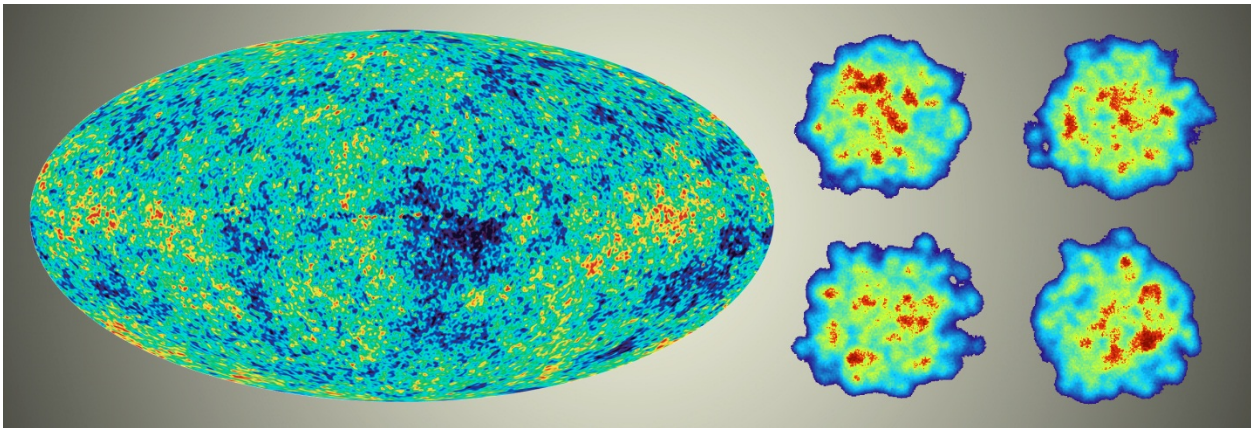


Figure II-5: Our one universe with its primordial fluctuations (parts per million variations in temperature) as measured via photons by the WMAP satellite experiment (left) compared to seed fluctuations (corresponding to 10-15% variations in temperature) in four simulated heavy ion collisions at RHIC (right). The measured fluctuations bring us knowledge about the quantum fluctuations at the earliest moments of the explosion (big bang or heavy ion collision) as well as about the material properties of the rippling fluid that ensues. Observations of the glow of the big bang or of heavy ion collisions reveal different and complementary properties of the trillions-of-degrees-hot matter that filled the microseconds old universe.

Quark-gluon plasma was created in the United States at RHIC, and it was there that we first learned of its near-perfect liquid nature. This discovery was the top physics story across all areas of science in 2005 according to Discover Magazine. Since that time, the experimental tools available have substantially expanded with the turning on of the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland, as well as with a ten-fold increase in beam intensity and new technology detectors at RHIC. RHIC was designed as a discovery machine with great flexibility. Its flexibility ensures that the coming decade will see discoveries answering questions not even imagined before RHIC was constructed. At the same time, a suite of precision measurements, including some that can only be made at RHIC, some that can only be made at the LHC, and some where the payoff comes only from combining measurements at both, are expected to provide fundamental insights as they follow up on discoveries made by RHIC in its first decade.

The Phase Diagram of Nuclear Matter

The manner in which quark-gluon plasma coalesces into protons and neutrons is characterized by the phase diagram of nuclear matter, depicted in the right panel of Fig. II-6. In the early universe, protons, neutrons and their antiparticles coalesced from a plasma consisting of almost as much matter as anti-matter, corresponding to the far left portion of the diagram. The theory of the nuclear interaction predicts that under such conditions, the transition is continuous, like the one that happened a few hundred thousand years later when the first atoms coalesced from a plasma of electrons and nuclei. In contrast, quark-gluon plasma containing a sufficiently large excess of matter over anti-matter may instead experience a sharp ("first order") phase transition as it cools, corresponding to the center and right-hand portions of the diagram where a sharp boundary between different phases is depicted as a black line. At the boundary, bubbles of quark-gluon plasma and bubbles of protons and neutrons coexist at a well-defined critical temperature, much as bubbles of steam and liquid water coexist in a boiling pot. At high enough pressures, however, water vapor condenses into a liquid continuously even though at ordinary atmospheric pressure there is a sharp transition. The separation between these two regimes is called a critical point and is indicated by the large dot at the end of the black line in the left panel of Fig. II-6. The phase diagram of quark-gluon plasma shown in the right panel is expected to exhibit similar behavior: at low enough excess of matter over antimatter the quark-gluon plasma condenses continuously into protons and neutrons while at high enough matter excess there may be a sharp transition, starting at a critical point. **It is not yet known whether nuclear matter has a critical point, nor where it might lie in the phase diagram,** as theoretical calculations are notoriously difficult when there is an excess of matter over antimatter. **Only experimental measurements can answer these questions definitively.** The theoretical calculations are advancing, however, with new methods and advances in computational power both anticipated. Recent theoretical progress together with the unique experimental capabilities offered by RHIC make for an unprecedented opportunity: to be able for the first time to map out the phase diagram of nuclear matter and connect it directly and quantitatively to the fundamental interactions of quarks and gluons—a project that could eventually unlock the secrets of matter, from the forging of the protons and nuclei that stars are made of in the Big Bang to the initial moments of supernovae explosions, to the exotic forms of matter that may be found in the hearts of neutron stars. **The experimental discovery of the critical point would represent a giant leap forward in our understanding of nuclear matter. It would provide a distinctive landmark in the mapping of its phase diagram.** It would also be direct experimental confirmation of the prediction that the transition in which protons and neutrons formed in the microseconds-old universe was continuous and it would furthermore confirm the existence of a sharp transition in the presence of a larger excess of matter over antimatter, with implications for very dense matter within neutron stars, for example.

The RHIC facility is uniquely positioned in the world to discover the critical point. Experimental discovery of a sharp transition beyond the critical point may also be within reach of RHIC and would be just as important, but its signatures are at present less well-understood and may be less distinctive than in the case of the critical point. In the past three years, RHIC has collided heavy nuclei at a range of different energies, starting to capitalize on its unique capability to make precise measurements with identical detector performance ("acceptance") for collisions whose energies vary by more than a factor of 20. As the collision energy is lowered, the protons and neutrons pile up and create quark-gluon plasma at higher net matter density (allowing the exploration of different regions of the phase diagram as indicated in Fig. II-6). The experiments see exciting hints of a possible transition in collisions with energies between 6% and 10% of the top energy accessible at RHIC. If the critical point indeed lies in this range, this discovery can only be made in the United States at the RHIC facility. To follow through and make definitive scientific conclusions, the accelerator experts are designing a procedure referred to as electron cooling to increase the beam intensity at these energies by more than a factor of ten. Targeted new detector capabilities will also increase the RHIC sensitivity to the expected signals of the critical point. If the critical point turns out to be at even higher matter excess, the RHIC program can scan to even lower energies and would then be in a race with future facilities (NICA in Russia and FAIR in Germany).

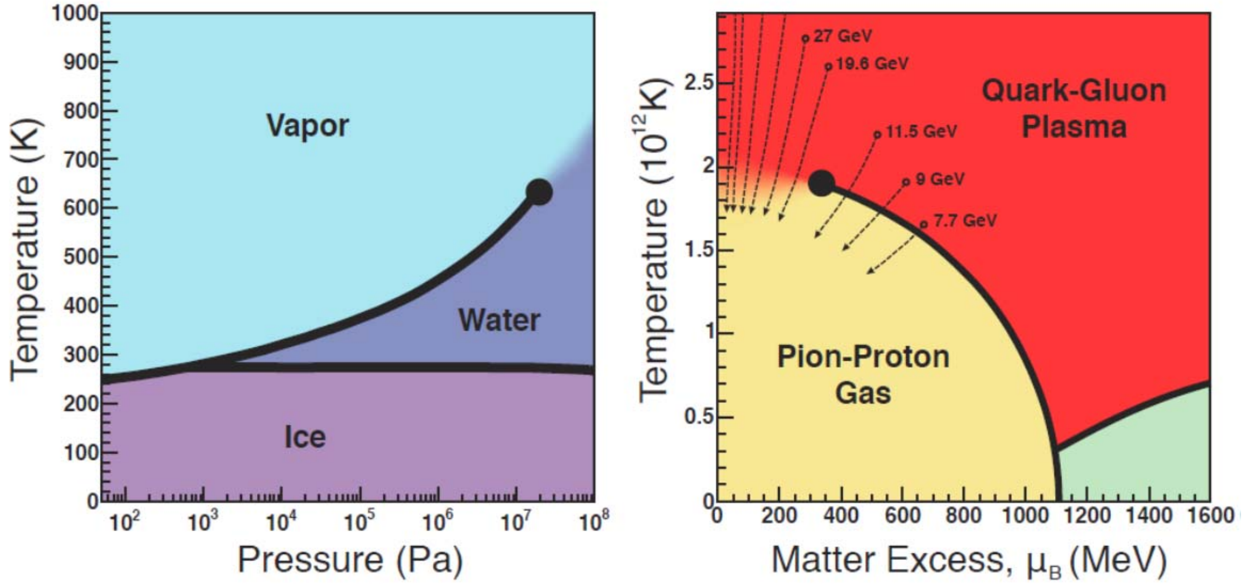


Figure II-6. (Left) Phase diagram for water. (Right) Phase diagram for quark-gluon plasma. Quark-gluon plasma made in heavy ion collisions at the top RHIC energy (200 GeV) and higher contains almost as much antimatter as matter, and so follows the left-hand edge of the phase diagram as it cools. Lower energy collisions make quark-gluon plasma with higher excess of matter over antimatter (parameterized by the "chemical potential μ_B") and so can be used to explore the phase diagram. The location of the water critical point shown as a solid black circle is known and was determined by experimental measurements. The location of the critical point in the quark-gluon plasma phase diagram is unknown; we have placed it where recent experiments at RHIC may be revealing hints of its presence. The green region contains superconducting forms of quark matter that may exist in the centers of neutron stars. The mapping of this phase diagram is just beginning; we know its features in the regions that we have colored red, yellow and green but at present we have no reliable knowledge of the location of any of the boundaries between these continents.

Quantum Fluctuations, Writ Large

We shall see below that discoveries made since 2010 have opened a path to direct experimental measurements of the quantum fluctuations in the nuclei incident in a heavy ion collision, which seed the formation and explosion of a droplet of quark-gluon plasma. Quantum fluctuations are also of great interest because they can sometimes violate fundamental symmetries, temporarily. For example, although they are exceedingly rare, the laws of physics admit the possibility of quantum fluctuations in which matter is turned into antimatter or vice versa. At high enough temperatures these kinds of fluctuations are thought to become frequent enough that they may play a key role in explaining the presence of matter and the absence of antimatter in the universe around us. However, the temperatures at which matter/antimatter asymmetric fluctuations become copious are about a thousand times hotter than those achievable in heavy ion collisions. Remarkably, quark-gluon plasma is nevertheless thought to feature very similar quantum dynamics, although the analogous fluctuations in quark-gluon plasma result in domains that violate mirror-reflection symmetry ("parity symmetry"), rather than matter/antimatter symmetry. In general, the laws of quantum chromodynamics operate in exactly the same way in a mirror image of the real world, but quantum dynamics in quark-gluon plasma makes transitory "parity-violating domains", whose character changes upon mirror reflection.

Several years ago, nuclear theorists predicted that the magnetic fields produced within heavy ion collisions (which are brief in duration but are a billion billion times stronger than the earth's magnetic field and more than a hundred times stronger than the strongest astronomical magnetic fields) would act on these transitory fluctuations in a way that could produce experimentally observable effects. In addition to being directly analogous to the higher-temperature processes that may have produced the excess of matter over antimatter in the universe responsible for our existence, these fluctuations and their interplay with magnetic fields are described by equations that are similar to those that describe electrons in graphene and "Weyl semimetals", materials at the frontier of modern condensed matter physics. In 2009, experiments at RHIC found the first possible signatures of parity-violating domains, and these signatures have now also been seen at the LHC. However, alternative interpretations of these pioneering measurements are possible. Earlier this year, RHIC reported preliminary low-statistics results consistent with three further predicted consequences of the presence of these fluctuations. One of these measurements relied on colliding non-spherical (uranium) nuclei—done for the first time in a test run this year at RHIC. The flexibility of the RHIC accelerator is allowing for control experiments with different nuclear geometries that change the interplay between the quantum dynamics and the magnetic field. A second of these measurements relied on systematically lowering the collision energy from the maximum to only about 4% of the top RHIC energy to map out the threshold for the original signature. **Control over both collision geometry and energy is unique to RHIC and relies upon its flexibility, putting the United States in the position to discover parity-violating domains. This makes RHIC the unique place for studying these quantum fluctuations, similar to those that may be responsible for the universe being made of matter today, instead of antimatter.** RHIC thus continues to serve up new discoveries and new concepts with ramifications well beyond nuclear physics.

Most Perfect Liquid in Nature

At the highest RHIC collision energy, measurements of photon emission indicate the creation of quark-gluon plasma with an initial temperature of about 4 trillion Kelvin, which is about twice the phase transition temperature. The theoretical expectation was that the matter would behave as a gas of quarks and gluons (in which the particles move large distances between collisions). However, the first data at RHIC already told a different story: the quark-gluon plasma expands and flows like a perfect liquid, with almost no internal friction. This discovery was like lighting a match to a fuse, igniting new ideas and insights in far-flung corners of science that had not previously had fruitful connections with nuclear physics.

Although we only have experimental access to one Big Bang, the quark-gluon plasma formed in nuclear collisions can be created over and over again, and we have the ability to create these mini-verses with different geometrical configurations. One can arrange droplets that are circular or elliptical, for example. In a circular configuration, the droplet explodes outwards in a radial pattern. In contrast, in the elliptical geometry, there are larger forces along the shorter axis and because it is such a perfect liquid the matter explodes with much greater force in this direction than along the longer axis. These explosion patterns are measured by precision tracking of the thousands of particles that come out in a spray as the quark-gluon plasma falls apart. The observed patterns indicated an outward flow pattern as expected from a flowing liquid with almost no losses due to internal friction. This, in turn, signals that the liquid is remarkably "strongly coupled", meaning that each bit of fluid is so well connected to its neighbors that when the liquid flows, even in an asymmetric pattern, it does so with little internal friction.

In a completely unanticipated development, sparked by theoretical work of nuclear physicists in the United States, physicists realized that many theories bearing QCD-like features manifest strongly coupled liquids that have a string theory dual description. In these theories, the formation of quark-gluon plasma maps directly onto the formation of a black hole in a higher dimensional gravitational space. And, any such liquid has a universal, and very low, value of its "imperfection index", the parameter that describes how much momentum is dissipated as heat as a droplet of the liquid explodes. These liquids are unusual in that it is as if the coupling between one bit of the fluid and its neighbors is infinitely strong. Of all the liquids we know, quark-gluon plasma flows with the least dissipation, meaning that it comes closest to the universal value of the imperfection index; in this sense, it is the most perfect liquid we know. Remarkably, matter made of ultra-cold atoms (less than a millionth of a degree above absolute zero temperature) can be manipulated to have a similar near perfect liquid behavior to the primordial quark-gluon plasma, making it the second-most-perfect liquid we know even though it is 10,000,000,000,000,000,000 times colder! The calculations that delineate the properties of strongly coupled liquids originate in string theory, but their greatest utility to date has come from the qualitative and semi-quantitative insights they have provided into phenomena in heavy ion collisions. Nuclear theorists are now working on extending their application to the liquid of ultra-cold atoms and to various electronic "liquids" in condensed matter physics that are very challenging to understand.

It is a scientific imperative to determine the degree of fluid perfection precisely and, through that determination, to gain fundamental insights into the inner workings of quark-gluon plasma. It will be particularly interesting to discern whether quark-gluon plasma is a strongly coupled nearly perfect fluid at all temperatures accessible in collisions at RHIC and the LHC, or whether it only behaves this way near the phase transition and becomes somewhat more gas-like at higher temperatures. **How close is the imperfection index of quark-gluon plasma to the universal value?** If QCD itself has a dual description as some as yet unknown string theory, an answer to this question from heavy ion collision experiments translates into a quantitative characterization of this string theory. **Is the lowest imperfection index achieved right at the quark-gluon plasma transition temperature or over a broad range of higher temperatures? Is quark-gluon plasma the most perfect fluid realized in all of nature?** Combined measurements at RHIC and LHC are necessary to answer these questions. The LHC collides nuclei for four weeks each year (the rest dedicated to a different set of studies including the discovery of the Higgs particle) at energies a factor of more than ten above RHIC, and thus probes the highest temperature range. RHIC probes matter closer to the transition temperature and has a long reach to even lower temperatures and higher matter excess.

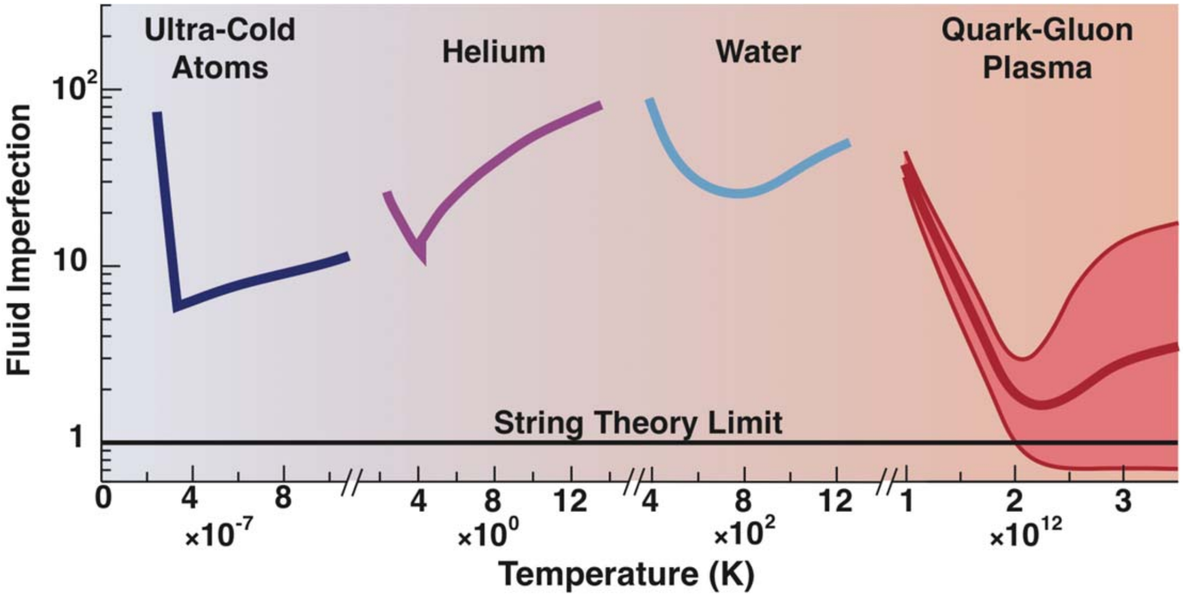


Figure II-7. The imperfection index of various fluids -- the lower its value, the less internal friction occurs within a liquid as it flows. Each liquid has a phase transition within the temperature range shown. The right panel describes QCD matter containing as many anti-quarks as quarks, zero matter excess, along the vertical axis of Fig. II-6. Not far above its transition, quark-gluon plasma has an imperfection index between 1 and 3 times the string theory limit. Future measurements will determine its imperfection more precisely and will show us how it changes with temperature, which is currently unknown. If liquid quark-gluon plasma has quasi-particles at higher temperatures, the imperfection index must rise rapidly.

As mentioned previously, the dominant shape of the initial quark-gluon plasma is typically circular or elliptical. However, as shown in Fig. II-5 there are significant quantum fluctuations that seed hot and cold spots dotting the volume. Until recently it was thought that diffusion (smearing of energy due to thermal agitation) would simply erase any evidence of these fluctuations. However, due to the almost perfect liquid behavior, these fluctuations have been shown to survive the explosion of the quark-gluon plasma and leave imprints that are accessible to experimental investigation and therefore provide sensitive measures of the fluid imperfection. Data reported recently from both RHIC and the LHC show great promise that these seed fluctuations can be measured in the next few years, in concert with pinning down the perfect liquidity.

The new Electron Beam Ion Source (EBIS) now completed at RHIC (in part also funded by NASA for biological studies on cosmic ray exposure for space travel), allows almost any nuclei to be accelerated. This provides a new and necessary ability to choose the geometry of collisions at RHIC, making it possible to tailor the initial shapes of the collisions in unprecedented ways by colliding non-spherical nuclei like uranium and colliding different size nuclei to obtain asymmetric shapes. Before these experiments, the only way to obtain elliptical shapes was to pick collisions that were not head-on. However, this also has the undesirable effect of reducing the density of the quark-gluon plasma. The new capabilities at RHIC, capabilities that are not foreseen at the LHC, allow for separate control of the shape and density of the droplets, which will result in a data-driven reduction in the current systematic uncertainties in the determination of the fluidity of quark-gluon plasma. **New experiments that provide new observables have just opened the door to characterizing not only the properties of quark-gluon plasma itself but also the quantum fluctuations seeded within it at its moment of creation.**

This physics of quantum fluctuations in the initial creation of the mini-verse quark-gluon plasma relates directly to a theory that the nucleus just before the collision is not best described as a container of protons and neutrons, or even of quarks and gluons. Instead, just as particles of light (photons) are sometimes better described as waves (for example the refraction of light), there are circumstances where it is best to think of the nucleus as a single fluctuating wave of gluon fields. These gluon fields are sometimes called Color Glass Condensate. A key method of studying this physics is through proton-nucleus collisions, where quark-gluon plasma is not formed, allowing the isolation of effects of the initial gluon waves. Initial RHIC measurements have found effects that may be caused by the presence of these gluon waves. Upcoming measurements at RHIC of proton-nucleus collisions made possible by recent upgrades to the accelerator and even higher energy collisions coming soon at the LHC will sharpen our view. In addition to the fundamental study of these gluon fields, the new insights will help to constrain our understanding of the seed fluctuations in nucleus-nucleus collisions that create quark-gluon plasma. A future Electron Ion Collider would be the best tool with which to do a systematic exploration of the new regime that we are starting to explore with proton-nucleus collisions.

Quasiparticles in Quark-Gluon Plasma

We often think of objects as simply being composed of individual particles such as atoms. However, many systems have collective excitations that can be thought of as the motion and interaction of "effective particles" (often termed quasiparticles). Much of semiconductor or metal physics, for example, is built upon the notion that rattling around within a semiconductor or a metal are quasiparticles that are in some ways like electrons but which have quite different masses and interactions. More exotic examples abound in condensed matter physics. For example, materials that exhibit the fractional quantum hall effect feature quasiparticles with a fraction of the charge of an ordinary electron (for which the 1998 Nobel Prize was awarded). As an archetypal example, the essence of superconductivity arises from the binding of electron-like quasiparticles into pairs (referred to as Cooper pairs). In a flowing liquid, dissipation arises if any independent quasiparticles can break free from the collective motion of the fluid; this costs energy and disrupts the correlations in the perfect liquid. The extraordinarily low dissipation in quark-gluon plasma, when quantified sufficiently precisely, implies that the quarks and gluons are so strongly interacting that the liquid cannot break apart into individual quasiparticles as it flows. This highlights how astonishing the liquid-like character of this primordial phase of matter is. At the same time, we know that if we had a microscope that could image quark-gluon plasma with very high spatial resolution we would find that this apparently featureless strongly coupled liquid is indeed made of quarks and gluons at short distances. We know that when we crank up the resolution of a microscope, we see finer and finer details (as illustrated in Fig. II-8). We need a "microscope" that allows us to see the quarks and gluons within the liquid quark-gluon plasma. Just seeing them is not enough, however. **The challenge is to understand how from ordinary interacting quarks and gluons a liquid emerges that is so strongly correlated that it cannot be broken into individual quasiparticles and must flow smoothly.** Addressing this challenge could teach us about the emergence of many other phenomena in strongly interacting systems in condensed matter physics.

The key, from an experimental point of view, is to find "microscopes" with varying resolution that allow us to characterize quark-gluon plasma at varying length-scales. Because a droplet of quark-gluon plasma does not sit still for long enough to point an electron beam or any other kind of external microscope at it, we must find ways to use probes produced within the heavy ion collision itself for microscopy.

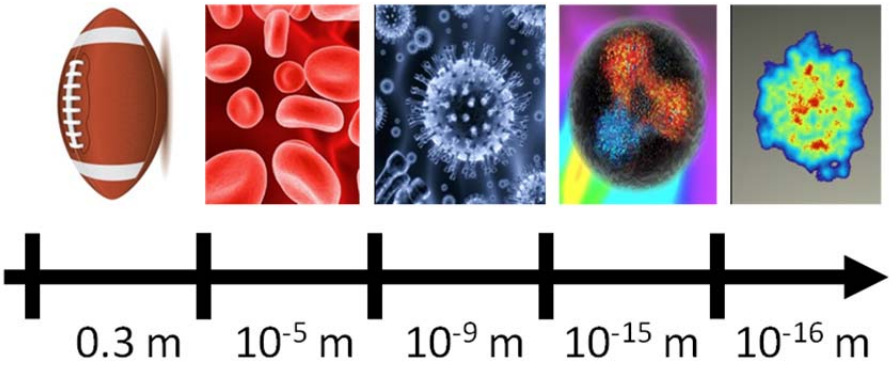


Figure II-8. Matter has different structure when imaged using "microscopes" with different resolution. From left to right, matter as seen with the naked eye, with a light microscope, with an electron microscope, a cartoon image of the interior of a proton, and a simulation of fluctuations in a heavy ion collision. RHIC is a microscope that can see the ripples in the liquid quark-gluon plasma seeded by these fluctuations. Via measurements that give RHIC higher resolution, it can see the quark and gluon quasiparticles within the liquid.

In the collision of two nuclei, most of the energy goes into creating the very hot quark-gluon plasma. However, there can in addition be an exceptionally energetic collision between two individual quarks within the nuclei. In this case, the two quarks will be shot away from their hard collision at high energy and in nearly opposite directions. These high energy quarks then serve as the "microscope", probing the quark-gluon plasma as they traverse it. Sometimes there will instead be a high energy photon (a particle of light) recoiling in the opposite direction to a high energy quark. In this case, the quark-gluon plasma is effectively transparent to the photon. Thus, by the precise measurement of the photon energy, one knows the initial energy of the opposing quark. In that way, the "microscope" on the quark-gluon plasma is calibrated. This approach is inspired by the many ground-breaking discoveries made via analogous microscopy with lesser resolution. Rutherford shone a beam of particles through gold foil and saw the gold nuclei within; today, we shoot quarks with calibrated high energies through quark-gluon plasma looking for the quasiparticles within.

A fundamental question to be answered is how a high energy quark interacts with quark-gluon plasma and how this depends on the temperature of the plasma and the resolution scale being examined. The quark can lose energy by transferring it to the quark-gluon plasma via the analogue of friction or by radiating energy away as it scatters from the quark-gluon plasma. In the case of a perfect liquid with no quasiparticles this transferred or radiated energy can only be observed in sound or shock waves rippling through the quark-gluon plasma and heating it up. **Precise measurements of how quarks with different initial energies lose energy and of the way the "lost" energy is distributed in the plasma can illuminate the liquid nature of quark-gluon plasma and can determine the resolution scale at which the quark and gluon quasiparticle substructure is revealed.** The greatest scientific impact of this kind of microscopy will come at this resolution scale, not at arbitrarily high resolution, because we already know that at very high resolution we must see ordinary quarks and gluons while the challenge is to see how it is that they conspire to form a featureless liquid.

High energy quarks break apart into a spray of quarks and gluons and are measured in detectors as a cone-shaped spray of many particles called a "jet". When analyzed with sufficient precision, jets can be used as microscopes with different resolution scales. At the LHC, the high colliding energy creates quark-gluon plasma at a higher temperature and also increases the number of these high energy quark-quark and photon-quark pairs. In the earliest data taking at the LHC, experiments observed collisions where one jet so dwarfed the other that the other must have lost most of its energy to the quark-gluon plasma. There are initial hints that the LHC jets are reaching well beyond the resolution scale at which the granularity within the liquid plasma first comes in sight and also that the coupling of high energy quarks to the quark-gluon plasma may be stronger at RHIC where the plasma is closer to the phase transition temperature. Definitive answers will require comparison of precise jet measurements to come at RHIC and the LHC. At RHIC, these new measurements will take advantage of the recently completed intensity upgrade to the accelerator and possible future detector upgrades for high-rate jet measurements such as sPHENIX. In the future, with these two high powered microscopes aimed at the quark-gluon plasma we will unravel the temperature- and resolution-scale-dependent properties of this unique material.

Tracer Probes of Quark-Gluon Plasma

Direct microscopy of the constituents of matter (as detailed above with "jet" probes) is not the only way to learn about them. Einstein inferred the existence of atoms in fluids by analyzing much larger "tracer particles" whose Brownian motion he attributed to their being buffeted by individual atoms. The analogue of Einstein's approach can be pursued in liquid quark-gluon plasma, even though it contains no quasiparticles. In the earliest stages of a nuclear collision, pairs of charm or beauty quarks can be produced. These rare quarks are much heavier than the light quarks which lose their individuality in the liquid. A charm or beauty quark can be swept along with the fluid flow, and buffeted by the fluctuations in the fluid. But, once created it cannot be destroyed in the quark-gluon plasma. Thus, these quarks act like tracers, gauging the properties of the quark-gluon plasma as they diffuse through it. This is analogous to mapping out tumors with radioactive isotope tracers in people or mapping boreholes for likely nearby oil deposits using neutrons.

Measuring such heavy quark tracers is the top near-term priority of the program at RHIC. The RHIC collaborations have made major investments in state-of-the-art silicon detectors capable of measuring particle trajectories at the 0.005 centimeter level to tag particles containing charm and beauty quarks. Combined with the recently completed RHIC beam intensity upgrade, these new detectors are just now raising the curtain on this physics. **Over the next five years, precision measurements of these heavy quarks are expected to provide the best determination of the degree of liquid perfection.** The LHC is making complementary measurements of these heavy quarks at higher momentum, shooting them like bullets through the liquid, and CERN is considering detector upgrades needed to make similar measurements to those at RHIC in a higher temperature regime.

Occasionally, a heavy charm quark and charm antiquark can form a bound pair, much like a proton and electron can form a hydrogen atom. These bound states provide another opportunity to gauge the temperature of the quark-gluon plasma and measure its properties. If the temperature of the quark-gluon plasma is high enough, these bound states "melt" and one observes a deficit in their production. Just such a deficit has been measured by RHIC experiments for the J/ψ particle (a bound state of a charm and anti-charm quark). An exciting development is that at the LHC where one might naively expect a larger deficit due to the higher temperature, they actually observe more J/ψ particles. A likely explanation is that so many charm and anti-charm quarks are produced in a single LHC event that even though the J/ψ bound states do initially melt the charms can later find random anti-charm partners as the quark-gluon plasma breaks up. The new frontier in these measurements is of even heavier beauty/anti-beauty bound pairs. One reason is that there are three such bound states that are bound more or less tightly and so have different sizes. They are therefore expected to "see" the plasma with different resolution scales and to melt at different temperatures. Initial measurements at the LHC appear to follow the expected melting pattern. Measurements of the same three states at RHIC are critical to arrive at a unique interpretation of these data and, with high statistics benefitting from future upgrades, to **map out the temperature dependence of the melting process and see how the plasma behaves at three different resolutions.** This is an ambitious program that will push the newly upgraded RHIC detectors and accelerator to the highest levels of their anticipated performance.

Summary

By virtue of the investments, both intellectual and financial, made by the U.S. in the science of quark-gluon plasma over the past decade, this field is now at a moment analogous to superconductivity research just before the key measurements that let us see how a superconductor works or astronomy just after the Hubble telescope had taken its first high quality images. Because of the unique flexibility and capability of RHIC, critical regions of the phase diagram of quark-gluon plasma can now be explored and the dynamical processes that may be responsible for the excess of matter over antimatter in our universe can now be probed. And, RHIC and the LHC can now be used in concert to characterize the most perfect liquid in nature—how it moves and how it is assembled from its quark and gluon constituents. The U.S. has led this new field of science for its first decade and is poised to lead it in the decade to come, which promises to be an era of discovery, precision, and precision-enabled discovery.

D. Nuclear Structure, Reactions, and Nuclear Astrophysics

Introduction

The atomic nucleus is the core of visible matter comprising 99.9 percent of its mass; its structure determines many facets of the world around us. Atomic nuclei are nature's most abundant high energy-density substance. Nuclear processes fuel stars, determine stellar evolution, drive stellar explosions, and are responsible for the origin of the elements in nature. The subfield of nuclear structure, reactions, and nuclear astrophysics (NS/NA) attempts to measure, explain, and use nuclear properties and reactions to meet society's scientific curiosity and needs. The relevance of this science spans the dimensions of distance from 10^{-15} m (proton's radius) to 12 km (neutron star radius) and timescales from fractions of a second after the Big Bang to today, i.e., 13.7 billion years later.

The intellectual challenges for this field are captured well in **the four overarching questions** presented in the Introduction of this document. The specific challenge for NS/NA is to explain how atomic nuclei are created, how they behave, and how to use them for science and applications. Overcoming these challenges requires a deep understanding of the atomic nucleus. The vision of the field is to achieve this understanding by development and testing of a comprehensive theory of nuclei and their interactions that has predictive power and quantified uncertainties. Informed by experimental observations of important properties for key nuclei, this theory will enable us to answer some of the deepest questions about the evolution of the cosmos and the structure of matter. In particular, we will be able to pinpoint the astrophysical environment in which the heaviest elements were produced, thereby resolving a longstanding puzzle about how the visible matter of the universe evolved into what is observed today. This theory will also allow us to determine the limit on the number of neutrons and protons that can be packed into a single nucleus, search for tiny violations of fundamental symmetries that may signal the presence of additional forces of nature, and model the properties of fission products of uranium and plutonium isotopes relevant to nuclear energy production. Part of the challenge is to understand which nuclei are going to be the most interesting or important in realizing this vision, and then make them in the laboratory. Today, we have identified some of the important nuclei, such as those responsible for creation of about half of the heavier elements in nature, but we do not yet have the means to make them. An overview of the opportunities is given in the following sections.

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 are discussed in detail in the section on applications. Opportunities to advance this field play a critical role in attracting and training the next generation of nuclear science leaders needed by our national laboratories, industry, and academia.

In the U.S., the experimental work in this area of nuclear science is carried out at two national user facilities, ATLAS at Argonne National Lab and NSCL at Michigan State University, as well as a number of small accelerator laboratories at universities and national laboratories. Experimental work is closely coupled with forefront developments in nuclear theory and computational tools made by researchers employing the nation's top computational facilities. The breadth of the research requires multiple approaches with a variety of tools and techniques. The individual research groups are usually small, often involving many junior scientists and students who are responsible for all aspects of their research.

Our current understanding has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allowed individual experiments to be performed with only a small number of atoms. Concurrent improvements in theoretical approaches and computational science have led to a more detailed understanding and pointed toward which nuclei and what phenomena to study. However, to break current experimental barriers, and for the U.S. to remain at the forefront of this strategically important field, NS/NA needs expeditious completion of a new, powerful experimental facility—the Facility for Rare Isotope Beams (FRIB). With FRIB, the field has a clear path to achieve its overall scientific goals and answer the overarching questions. With FRIB, we will have the ability to produce the key isotopes now unavailable. FRIB will be the world's most powerful facility to explore the rare isotope frontier, making nearly 80% of the isotopes predicted to exist for elements up to uranium and providing access to beams of the most interesting isotopes. Furthermore, FRIB will make possible the measurement of a majority of key nuclear reactions to produce a quantitative understanding of nuclear properties, and will provide access to the rare isotopes important in astrophysical processes.

The Origin and Evolution of Atoms and Nuclei

The subfield of NS/NA participates in answering the overarching question **"How did visible matter come into being and how does it evolve?"** Nuclear astrophysics studies the nuclear and chemical evolution of the Universe since the beginning of nucleosynthesis following the Big Bang. By addressing the nature of the nuclear force, the mechanism of nuclear binding, and nuclear decays, the fields of nuclear structure and reactions describe the microphysics of this evolution.

Nuclear astrophysics is broadly concerned with nuclear processes in all astrophysical environments, giving us the tools to understand the nuclear and chemical evolution of the Universe, fundamental physics, and astrophysical observations taken with large telescopes and neutrino detectors. The build-up to the present mix of elements from the soup of free nucleons early in the Big Bang has occurred through complex nuclear reaction chains in many generations of stars. Carl Sagan summarized this remarkable series of events with his famous expression: "We are made of star stuff." There are open questions that will guide nuclear astrophysics in the coming decade. How did the elements and isotopes originate in the cosmos? What makes the stellar explosions we call supernovae, novae, or X-ray bursts? What is the nature of neutron stars? What can neutrinos tell us about stars? What were the first stars in the Universe like? Answering these questions requires understanding the structure of both stable and unstable nuclei.

A particularly significant role of nuclear astrophysics is to develop new probes for nuclear processes that are occurring in the deep cores of stars, not otherwise accessible through traditional astronomical techniques. This ranges from the observation of neutrinos from our sun and nearby supernovae by neutrino detectors located deep underground to satellite-based gamma-ray detectors mapping the distribution of radioactive elements in our galaxy. Observations of neutrinos originating from the solar core complement helioseismological measurements of the surface of the Sun. The analysis of stellar pulsations provides information on the temperature conditions of the inner layers of massive stars during the later phases of their evolution.

A broad experimental portfolio has been developed to advance our understanding of the life and death of stars and to benchmark the increasingly sophisticated computer simulations of these events.

Nuclear reactions that determine the stellar energy production, lifetime, and the chemical composition have extremely low cross sections (a quantitative measure of the probability of a reaction occurring) and their study is handicapped by interference from cosmic ray backgrounds; these measurements are being pursued at deep underground laboratories to mitigate this interference. Another frontier is the study of nuclear processes that drive stellar explosions. These explosions occur on a rapid timescale of a few seconds. Radioactive nuclei formed in the explosion cannot decay within this short period and become part of the sequence of nuclear reactions that occurs far beyond the limits of nuclear stability (see Fig. II-9, top). A study of these reactions and 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. As discussed below, experimental data from FRIB will make it possible to identify the specific nature of the nuclear reaction pathway during an explosive event and, in turn, through comparison with the emerging abundance distribution, specifics about the astronomical site and conditions during the explosion. FRIB will be the premier machine with which to probe the nuclear physics of the explosive processes through studies of short-lived radioactive nuclei.

To explain the process of creating new atomic nuclei (nucleosynthesis), FRIB will investigate the most important nuclear reaction chains in stellar explosions associated with different astrophysical environments. Two examples illustrating this potential are X-ray bursts and supernovae. The first is driven by accretion of hydrogen fuel in binary star systems onto a compact star, either a white dwarf or neutron star. These events are observed as novae or X-ray bursts, respectively, and are thermonuclear explosions of the accreted hydrogen fuel on the surface of the compact star. The second kind of explosion, supernova, is triggered by the collapse of the inner core of a massive star to a neutron star, a process that initiates a shock wave that traverses the outer layers of the star, generating conditions that lead to multiple nucleosynthetic pathways behind the emerging shock. Similarly extreme conditions are associated with the merger of two neutron stars.

X-ray bursts are powerful thermonuclear explosions that within a few seconds transmute the low-atomic-mass material in the atmosphere of the neutron star into a distribution of heavy elements up to mass 100 by the rapid-proton-capture (rp) process, a sequence of rapid proton capture reactions and β-decays responsible for the synthesis of many proton-rich heavy isotopes (Fig. II-9, top). The timescale of the burst, the endpoint, and the final abundance distribution depend upon the nuclear reaction and decay rates along the rp-process path. Measurements of the reaction cross sections require higher beam intensities than are available at existing radioactive beam facilities. FRIB provides the necessary intensities for most of the critical rp-process nuclei (Fig. II-9, bottom). Therefore, for the first time, nuclear astrophysicists will be able to directly study radiative capture reactions to determine ignition conditions, timing, and endpoint conditions in these thermonuclear explosions.

How were the neutron-rich elements heavier than iron made? These heavy elements are produced either by slow neutron capture reactions, the s-process that takes place during helium and carbon burning phases of stellar evolution, or by rapid neutron capture reactions, the r-process that requires a much higher temperature and density environment (Fig. II-9, top). The traditional model for the r-process defines the r-process path shown in Fig. II-9. In the framework of this model, 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. From first experiments at existing facilities, such as ATLAS, on isotopes approaching the r-process path we know these extrapolations are highly uncertain and new experiments are required to measure directly the masses of crucial nuclei along the path.

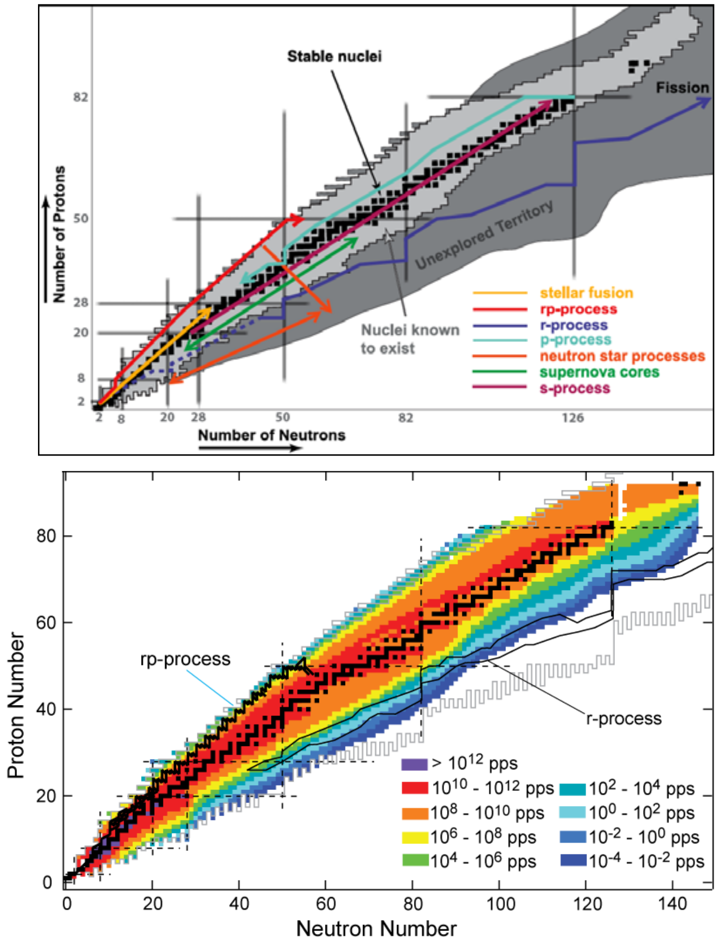


Figure II-9. Top: Schematic outline of the nuclear reactions sequences that generate energy and create new elements in stars and stellar explosions. Stable nuclei are marked as black squares, nuclei that have been observed in the laboratory as light gray squares. The horizontal and vertical lines mark the magic numbers for protons and neutrons, respectively. A very wide range of stable, neutron-deficient, and neutron-rich nuclei are created in nature. Many nuclear processes involve unstable nuclei, often beyond the current experimental limits. (Adapted from a figure by F. Timmes, Arizona State University.) Bottom: The chart of the nuclides in terms of the production rate of radioactive nuclei with FRIB. The color code is in particles per second (pps). (Courtesy of B. Sherrill and O. Tarasov.)

New constraints are coming from large aperture observatories such as the Hubble Telescope and Subaru. Observations of early-generation stars indicate a heavy-element abundance distribution, which matches the patterns, albeit not the absolute abundances, of the r-process element abundance distribution in our Sun. This strongly suggests that there is a unique type of astrophysical site for the r-process. However, the actual nature of this astrophysical site still remains uncertain and has been a matter of fierce scientific debate for many decades. Indeed, both the emerging shock front of a supernova and the clash of merging neutron stars could provide conditions for an r-process to occur. Interestingly, while the actual path and the subsequent decay feeding of the final abundances are different in the two cases, theoretical simulations of both scenarios provide abundance distributions that match the main features of the observed one. Nuclear physics data are thus crucial for removing the nuclear uncertainties when making detailed predictions for the path; hence, the actual site of the r-process. The r-process 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.

There have been heroic efforts over the last decades to expand theoretical and experimental frontiers in an effort to explain r-process nucleosynthesis. The increasingly complex models of (i) supernova explosions, taking into account detailed radiation/hydrodynamics, neutrino and nuclear physics, and magnetic and rotational effects, and (ii) merging neutron stars both motivate the pursuit of measurements beyond the present limits of experimental facilities. FRIB will provide the experimental reach and mass and lifetime data necessary to test the most important parameters of r-process simulations. It will test the suitability of the various nuclear models presently used for r-process simulations and will provide new benchmarks for the astrophysical models proposed for the actual r-process sites. Detailed impact studies have been performed recently to identify the most critical isotopes for benchmarking and testing the Standard Model for the r-process. To illustrate the sensitivity to binding energy, simulations were performed for a successful mass model (HFB-21). Figure II-10 shows the color-coded isotopes along the r-process path that are found to have the biggest impact on the final elemental abundances. Also indicated are the limits of reach for the present and future U.S.-based facilities for the study of neutron-rich nuclei: CARIBU at ANL and FRIB. With FRIB nearly all of the key isotopes can be reached.

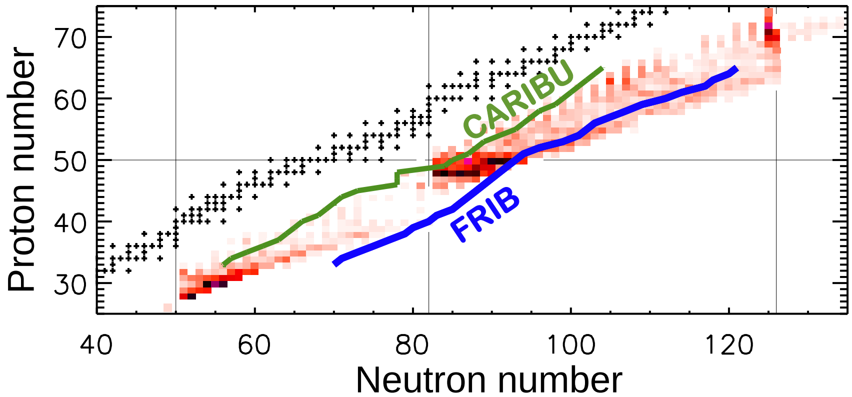


Figure II-10. Sensitivity of nucleosynthesis simulations in the r-process to binding energy predictions from a mass model. The darkly colored nuclei show the largest impact on the overall r-process abundance distribution as determined from variations of the neutron separation energy within 25% deviation from the respective mass model predictions. The two lines indicate the limits of reach of CARIBU (green line) and projected for FRIB (blue line). (S. Brett et al., will appear in Eur. Phys. J. A.)

FRIB will also be important for understanding various astrophysical objects. Neutron stars serve as a good example. The cooling behavior of transient neutron stars is determined by the energy budget of the nuclear processes on the ashes of the rp-process. Electron-capture reactions, driven by the ever-increasing density of the neutron-star crust, drive the abundance distribution to the neutron-rich side. Such electron-capture reactions change the internal energy budget in the crust and affect the cooling behavior of the neutron-star crust matter. These electron-capture processes can be studied by means of charge-exchange reactions on neutron-rich isotopes at FRIB, illustrated as "neutron star process" in Fig. II-9.

The Grand Nuclear Landscape

What combinations of neutrons and protons can form an atomic nucleus? The answer has important consequences for nuclear structure and astrophysics. The quest for the limits of nuclear binding is closely connected to the roadmap to a comprehensive theory of all nuclei and, as discussed earlier, to the question about the origin of elements in the universe. The territory of nuclear existence is currently unknown, but likely much more vast than we have explored so far. Only 288 of several thousand nuclides, or isotopes, known to inhabit the nuclear landscape are either stable or practically stable (i.e., have half-lives longer than the expected life of the solar system). By moving away from the region of stable isotopes, by adding nucleons (either neutrons or protons), one enters the regime of short-lived radioactive nuclei, which disintegrate by emitting beta and alpha particles, or split into smaller parts through the process of spontaneous fission. Nuclear existence ends at the drip lines, where the last nucleon is no longer bound to the others. Remarkably, the neutron-rich boundary 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 − *the nuclear landscape proper*. Today, about 3000 nuclides are known to us, but the number of those which have been well characterized is much less, see Fig. II-11 (dark blue).

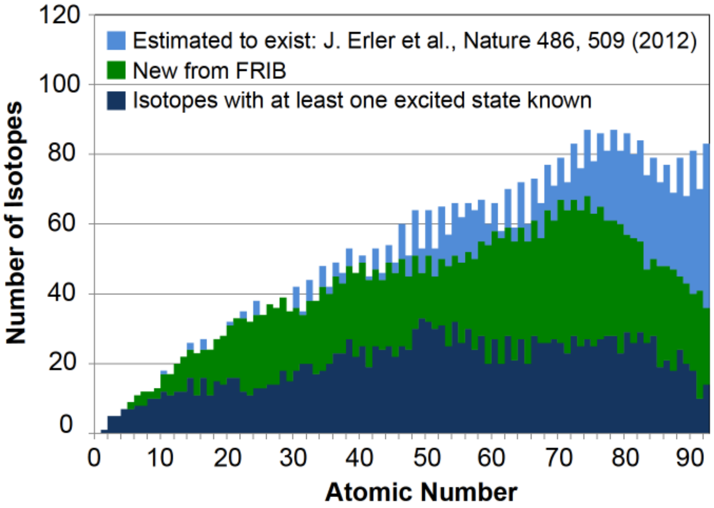


Figure II-11. Isotopes in the nuclear landscape. With its fast and reaccelerated beams FRIB will allow the broadest range of isotopes to be studied.

Nuclear theorists predict the existence of more than double the number of known nuclei (Fig. II-11). As discussed earlier, while most of the predicted nuclei may never be seen, their influence will certainly be noticed, as the astrophysical processes that generate many heavy elements occur relatively close to the driplines. Explaining how the atomic nucleus ticks, will require building a comprehensive model that describes quantitatively and predictably this quantum system, and is grounded in the fundamental interactions at play between its constituents (see Sec. E). Such a theoretical "bottom-up" description can be gained from an accurate solution of the nuclear many-body quantum problem, but this is a formidable challenge that can only be attacked with experiment and nuclear theory working in concert. To arrive at a comprehensive understanding of nuclei will require new insights from experiments on rare isotopes previously not available that will guide new theoretical developments. Accurate solutions of the strongly interacting nuclear systems will yield new insights and the ability to calculate phenomena, processes, and states of matter that are difficult or impossible to measure experimentally, such as in the crust of a neutron star or the core of a fission reactor.

The territory of very neutron-rich nuclei is where most of the action is in NS/NA research (r-process studies, probing the neutron drip line, and – generally – studying properties of neutron-rich matter as discussed below). Experimental exploration of this vast area is extremely challenging because of the very low production rates in studies involving the fragmentation of stable nuclei and the separation and identification of the products. With its high-power beams and highly efficient and selective fragment separators, FRIB will meet this challenge by delineating most of the neutron drip line up to $Z \approx 40$ (Fig. II-11, green) and exploring nuclear properties over a vastly increased range. Staking out the nuclear landscape also opens up opportunities to design nuclei with specific properties adjusted to our research and application needs.

There is another limit that challenges our present understanding of nuclei. What are the heaviest nuclei and atoms that can exist? Do very long-lived "superheavy" nuclei with atomic numbers greater than $Z=106$ exist in nature? While it was recognized long ago that, in spite of the huge electric repulsion between all those protons, the binding that comes from motion of protons and neutrons in regular orbits ("shells") could tip the balance in favor of their existence, precise calculations are difficult. The recent progress in this field came from the realization that new elements can be synthesized by using targets of very heavy elements such as berkelium (produced at the ORNL's High Flux Isotope Reactor) with neutron-rich beams. This novel approach was used by scientists in Russia and U.S. to create nuclei with $Z = 113$-118, having increased lifetimes, in accord with theoretical expectations. Another exciting avenue is offered by atom-at-a-time chemistry studies of the superheavy elements. 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 (Cn, $Z = 112$) it has been possible to place Cn in group 12 of the periodic table, under Mercury, Cadmium and Zinc. How can we reach even heavier nuclei and more neutron-rich, long-lived systems? The new-generation high-current stable-beam accelerators will be helpful in making some new discoveries, in spite of excruciatingly low production rates. However, in order to explore new, more neutron-rich superheavy regions, accelerated beams of radioactive neutron-rich nuclei will have to be utilized. One of the possible options would be to use collisions involving radioactive neutron-rich nuclei. FRIB could help in this quest by exploring mechanisms by which heavy and superheavy nuclei can be produced in the laboratory.

The borders of the nuclear existence do not end at the proton and neutron driplines and the superheavy region. The territory of neutron-proton matter is much broader. *The grand nuclear landscape* includes the extended nucleonic matter, such as that found in the crust of neutron stars. Understanding these systems is also part of the challenge for NS/NA.

The Simplicity of Complexity

Complex systems often display surprising simplicities; nuclei are no exception. 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. The resulting emergent phenomena discussed in this report—such as appearance of shells, collective rotation, superfluidity, and phase transitions—are not sensitive to the details of the interactions between the constituent particles. The relevant overarching question addressing the origin and nature of the nuclear emergent behavior is "**How does subatomic matter organize itself and what phenomena emerge?**" This perspective, focused on a highly organized complex system exhibiting special symmetries and regular patterns, is complementary to the "bottom-up" view discussed in the previous section.

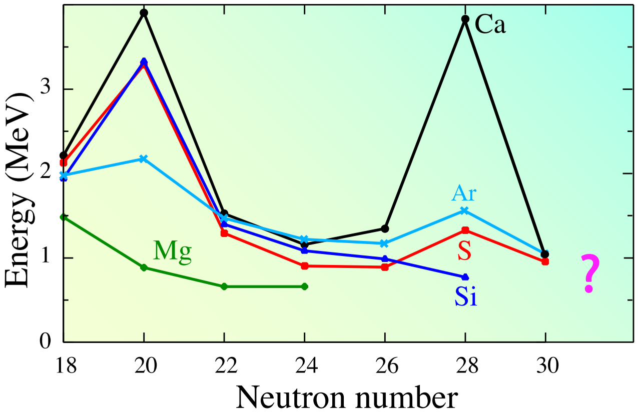


Figure II-12. Measured energies of the lowest 2^+ states in the neutron-rich even-even Mg, Si, S, Ar, and Ca isotopes. A high value indicates a magic number. Low values signal the development of collective behavior. The plot indicates that the traditional N=20 and 28 magic numbers vanish in rare isotopes (Courtesy of A. Gade)

One of the paradigms of nuclear structure is the shell model of the atomic nucleus, in which the motion of each neutron or proton is governed by a common force generated by all of the other nucleons. Thanks to this common force, similar to an electron's motion in an atom, nucleonic orbits bunch together in energy, thereby forming shells, and nuclei having filled nucleonic shells (nuclear 'noble gases') 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. One of the most dramatic series of discoveries with current rare isotope research has been the recognition that the traditional benchmark magic numbers are not the immutable cornerstones they were thought to be for over half a century during which nuclei were studied within a rather restricted range of neutron-to-proton ratio. This is exemplified in Fig. II-12, which shows the disappearance of N= 20 as a magic number in magnesium, and N = 28 in silicon, by the sudden reduction of the energy of the first excited state. Other experiments demonstrated that N=16 is a magic number in oxygen-24 (Z=8). These discoveries demonstrate the need for dramatic revision of the textbook knowledge of the motion of protons and neutrons inside the nucleus. In the superheavy region, there is no consensus with regard to what should be the next magic nucleus beyond lead-208 (82 protons and 126 neutrons). Calculations suggest fairly broad regions of enhanced stability, but we may well find surprises as we get there.

Excellent tests of nuclear shells were offered by recent studies of the proton-magic nickel (Z=28) and tin (Z=50) isotopes. The short-lived isotopes nickel-78 (N=50), tin-100 (N=50), and tin-132 (N=82), are expected to be rare examples of new doubly-magic heavy nuclei. While tin-132 was shown to behave as a good doubly-magic nucleus, the data around tin-100 and nickel-78 have led to surprises. The new structural information indicates that poorly understood forces that depend on the neutron-proton imbalance, and the poorly known forces involving three nucleons, may be in play. An important consequence of shell variations far from stability is their influence on astrophysical processes and on stellar nucleosynthesis. Progress will only be achieved by measuring properties of rare isotopes in key regions of the nuclear chart. Such structural data are an essential guide: they will help constrain the essential interactions, many-body correlation effects (such as nucleonic pairing, or superfluidity), and quantify the role of a very poorly understood but ubiquitous effect of particle continuum found in weakly-bound nuclei. FRIB's world unique complement of fast, stopped, and reaccelerated rare-isotope beams over the full range of useful energies is essential to provide the data needed to constrain nuclear models at the limits of nuclear binding.

Neutron Rich Matter in the Cosmos and in the Laboratory

What is the nature of nucleonic matter consisting of a huge number of nucleons, such as that in the crust of neutron stars composed almost entirely of neutrons? To explain the nature of neutron-rich matter across a range of densities, an interdisciplinary approach is essential in order to integrate low-energy nuclear experiments with astrophysical theory, nuclear theory, condensed matter theory, atomic physics, computational science, and electromagnetic and gravitational-wave astronomy.

Protons and neutrons in atomic nuclei near the neutron-drip line where the nuclear binding ends experience a very different environment than their cousins in stable nuclei. This results in drip-line nuclei having a very different character than we are used to. In light nuclei, the weak binding can lead to the formation of a diffuse "halo" of neutron matter surrounding the more densely populated nucleus. 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.

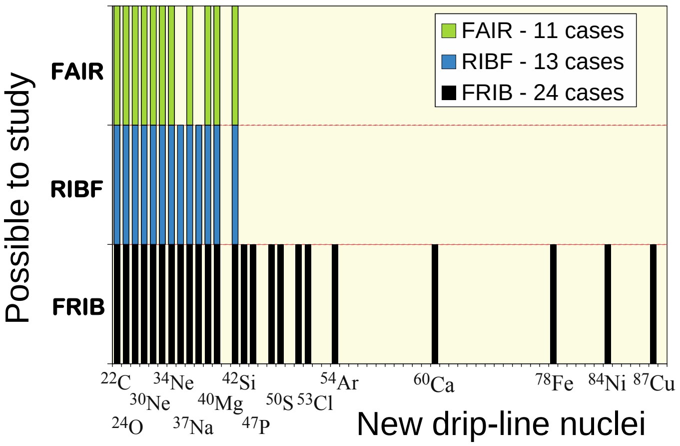


Figure II-13. The range of drip line isotopes to be studied at FAIR, RIBF, and FRIB with rates > 0.01particles/s (Based on NSAC 2007 Rare Isotope Task Force Report).

Close to the drip-lines, FRIB will provide intensities of rare isotopes sufficient to explore the properties of halos and skins, and to study the expected skin modes that could alter neutron capture cross sections important to r-process nucleosynthesis — thus providing unprecedented insight into nuclear structure at the extremes of neutron to proton ratio (see Fig. II-13). Often, the most sensitive and extreme tests for nuclear models are performed with the heaviest possible isotopes containing many neutrons in the skin. FRIB will nearly double the number of such nuclei that can be studied with sufficient detail and extend the reach from A=40 to A=90 or higher; it will be the only facility to access the key heavier nuclei – those beyond 42-Si.

Figure II-14 illustrates the multi-disciplinary nature of the quest for understanding neutron-rich matter on Earth and in the Cosmos. It shows the mass-radius relation for a neutron star predicted by various theoretical models. The typical mass of a neutron star is about 1.4 solar masses, and the typical radius is thought to be about 12 km. One of the main science drivers of FRIB is the study of a range of nuclei with neutron skins three or four times thicker than is currently possible. Jefferson Lab uses a faint signal arising from parity violation induced by the weak interaction to measure the radius of the neutron distribution of stable lead and calcium nuclei. Studies of neutron skins in heavy nuclei at both FRIB and Jefferson Lab, and investigations of high-frequency nuclear oscillations and intermediate energy nuclear reactions with a range of proton and neutron-rich nuclei will help pin down the behavior of nuclear matter at densities below twice typical nuclear density ρ_0. The relevant area open to these studies is indicated in light blue in Fig. II-14. At higher densities, relativity and the observation of a nearly two solar mass neutron star place severe constraints on the relationship between the pressure and density of nuclear matter, i.e., the nuclear matter equation of state.

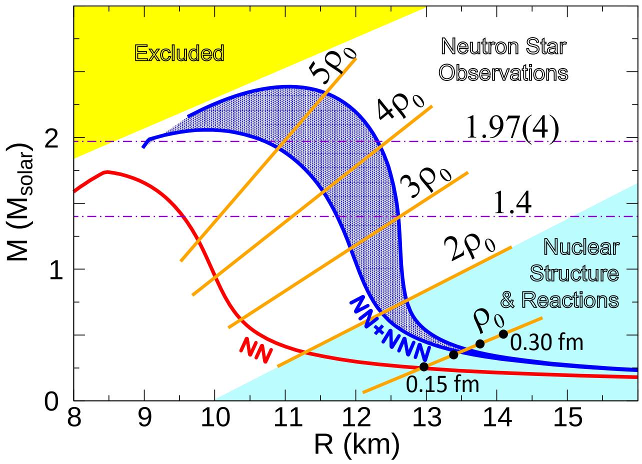


Figure II-14. Predicted relation between mass and radius of a neutron star modeled with forces involving two nucleons (NN) and forces also involving three nucleons (NN+NNN) (Gandolfi et al., PRC85, 032801 (2012)). The three-nucleon forces are both essential and poorly known, as indicated by a dark blue uncertainty band. The orange lines roughly indicate the predicted central density of the neutron star. The black dots mark the predicted values of the neutron skin in lead-208. The recent accurate measurement of a large neutron star mass M=1.97(4) M_{solar} in the system J1614-2230 provides a strong constraint on theoretical models.

Tests of Fundamental Symmetries

By producing isotopes with enhanced sensitivity to fundamental symmetries, opportunities, complementary to other sciences, are provided for discovering physics beyond the Standard Model. In this way, this part of the NS/FRIB program addresses the overarching question: **"Are the fundamental interactions that are basic to the structure of matter fully understood?"**

The "superallowed" beta-decays of nuclei in which both the parent and daughter nuclear states have zero angular momentum and positive parity are a case in point. In 2008, the Nobel Prize for Physics was awarded to Kobayashi and Maskawa, whose theory has become an important ingredient of our understanding of the subatomic world. The main assumption behind their theory was that the weak force is universal for the complete panoply of subatomic particles. To check this assumption, atomic nuclei proved to be the key. 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. The important advance came when the results of combined nuclear measurements worldwide, augmented by theoretical corrections, showed that a key part of the weak force is the same within 1 part in 10 thousand for the 13 different nuclear decays studied. Future measurements in heavy nuclei with A>62, where the theoretical corrections are largest, will be helpful in still reducing the remaining uncertainty.

As discussed in the section on fundamental symmetries, measurement of an electric dipole moment (EDM), which separately violates parity and time-reversal invariance, is one of the crucial probes of physics beyond the Standard Model. Heavy radioactive atoms hold promise as a sensitive place to search for EDMs. An enhancement of order 100-1000 (or more) is possible in nuclei, which have pear-like shapes, such as radium-225. One of the near-term goals of the field is to identify the best candidates for enhancement. Once operational, FRIB will provide an intense source for all of the viable candidates and provide at least an order of magnitude greater sensitivity than projected for current experiments.

Breadth and Relevance

The subfield of NS/NA has relevance to many branches of science and technology beyond the importance to astronomy, astrophysics, and fundamental symmetries discussed earlier. The deep connections of the nuclear many-body problem to the physics of complex systems that permeates modern science are as old as the field itself. Many examples, including superfluidity, superconductivity, collective excitations, symmetry-breaking phenomena, phase-transitional behavior, and chaos have been discussed in the 2007 LRP and the two most recent National Research Council decadal studies. Of particular importance are the connections to cold fermion atomic condensates, which share many common features with neutron matter. FRIB, with its potential to explore weakly-bound nuclei with a large proton-to-neutron imbalance, will offer many unique opportunities for interdisciplinary research. Study of nuclei near the driplines, neutron-rich nuclei of mid to heavy mass, and nuclei along the N=Z line will provide the necessary experimental input to gain a quantitative understanding of nucleonic superfuidity, probed through a variety of reactions that add or subtract pairs of nucleons. The understanding of the structure and decays of rare isotopes at FRIB, will lead to important progress in the general quantum science of open and marginally stable systems.

More broadly, U.S.-based low-energy research with rare isotopes will provide important benefits to society. In this way, this field answers the overarching question **"How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?"** Rare isotopes are used in a wide variety of applications ranging from medical diagnostics to the tracing of groundwater migration patterns. They serve as sensitive probes in materials science studies of nanoscale devices and mechanical wear in novel materials. Their properties are relevant to new, safer nuclear reactors with less waste produced, based, for example, on thorium or other technologies. The IAEA has pointed out that data on decay heat are needed to optimize these designs and safety measures. For human health, the use of radioisotopes in medical imaging and therapy has impacted the lives of millions of patients worldwide. New medical diagnostics and treatments enabled by ready access to a wider range of isotopes could be transformative.

E. Fundamental Symmetries and Neutrinos

Protons, neutrons, and atomic nuclei provide an ideal "laboratory" for testing fundamental forces that govern how matter interacts and how the universe has evolved. The subfield of nuclear physics that studies fundamental symmetries and neutrinos exploits this laboratory to perform precise tests of our current best model of sub-atomic interactions, known as the "Standard Model", while also searching for new physics and phenomena beyond our current understanding. The Standard Model, a theoretical framework that unites the basic sub-atomic interactions from the smallest to the largest scales of both length and energy, has proven extraordinarily successful over the past forty years, repeatedly being tested by increasingly sensitive experimental measurements. However, there are both compelling theoretical grounds and convincing experimental observations indicating that our understanding of fundamental forces is incomplete. Researchers in nuclear science are leading key components of the quest to determine just what the Standard Model is missing.

The study of fundamental symmetries and interactions, and the physics of neutrinos, is not solely within the realm of nuclear science. Though it spans a wide range of disciplines within the physical sciences, including high energy physics, atomic physics, cosmology, astrophysics, and astronomy, nuclear scientists lead when nucleons, nuclei or nuclear techniques are involved. The priority of this research program within nuclear science and its significance beyond the field was captured in Recommendation III of the 2007 LRP which stated: **We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.**

The targeted program of experiments seeks to address two of the key science questions called out in the recent NRC2012 report on nuclear physics:

- **How did visible matter come into being and how does it evolve?**
- **Are the fundamental interactions that are basic to the structure of matter fully understood?**

We live in a universe with an excess of matter, which is necessary for the existence of atomic nuclei, stars, and planets as we know them. The Standard Model cannot explain how the universe ended up today with more matter than anti-matter, i.e., why didn't the early universe produce equal amounts of matter and antimatter? The Standard Model is similarly unable to account for the quantum nature of gravity, to explain why the interaction responsible for radioactive decay flagrantly violates mirror symmetry (a.k.a. Parity), or why the electric charges of elementary particles like the electron come in well-defined discrete units or quanta. Thus, the early universe must have heeded additional laws of nature that are less apparent today. Uncovering those laws remains a compelling quest at the forefront of basic research, spanning multiple disciplines.

Against this backdrop, the targeted program of fundamental symmetry tests and neutrino studies identified in the 2007 LRP consists of four broad components that aim to answer the aforementioned key questions. Table II-1 below summarizes the components, the compelling scientific questions, and the experiments designed to answer them.

Electric Dipole Moment Searches • *Origin of Matter* • *New Forces* Exp’ts: nEDM	**Neutrinoless Double β-decay Searches** • *Nature of the Neutrino* • *Origin of Matter* Exp’ts: CUORE, EXO, MAJORANA → Tonne
Electron & Muon Properties & Interactions • *New Forces* • *New subatomic particles* Exp’ts: MOLLER, SoLID, Muon g-2	**Radioactive Decays & Other Tests** • *New Forces* • *Neutrino mass* Exp’ts: KATRIN, Nab

Table II-1. Four broad components of the nuclear physics program of fundamental symmetry and neutrino studies. The primary scientific questions addressed by each are given in italics. The proposed and on-going flagship experiments in each area are listed. The tonne scale neutrinoless double β-decay experiment would follow the current generation of measurements.

This program and the excitement it inspires are fueled, in part, by recent achievements and bright prospects for new discovery and insight. A decade ago there was such a fundamental breakthrough—measurements by both nuclear and high energy physicists in independent experiments definitively demonstrated that neutrinos, elusive sub-atomic particles associated with the weak interaction, possess tiny, but non-zero, masses. This discovery overturns the Standard Model assumption that neutrinos are massless. Furthermore, a precision measurement of another fundamental particle, the muon, in a magnetic field, indicated additional deviations from Standard Model predictions. Consequently, we must develop a "new Standard Model" guided by improved experiments and theoretical advances if we are to answer the questions posed above.

The research in Table II-1 falls into two broad areas—precision tests of the Standard Model and searches for new phenomena beyond the Standard Model. Experiments in the first category typically measure an observable quantity that can be compared to a calculated value from the Standard Model. Experiments in the latter category search for phenomena explicitly forbidden by the Standard Model or that require violation of a basic underlying symmetry principle. The distinctive character of nuclear scientists’ approach to these questions is harnessing neutrons, protons, and nuclei or their decay products as "laboratories" to provide enhanced experimental sensitivity or reach. Nuclear scientists capitalize on their understanding of basic nuclear processes to minimize unwanted background events and other systematic effects that limit sensitivity.

Nuclear science studies of fundamental symmetries and neutrinos are performed at a wide variety of facilities, including accelerators, reactors, and underground laboratories. While some studies will be conducted at nuclear physics facilities, in many cases experiments are located at facilities supported outside the field. The technical challenges of these high precision measurements require substantial research and development, pushing the bounds of technology, while often providing advances or applications that benefit society.

Below is described the vigorous program in fundamental symmetries and neutrinos that is currently underway and *led* by U.S. nuclear scientists, and the next generation of studies, bearing in mind the dynamic nature of the subfield and the likelihood that important new directions may emerge.

Why is there more matter than anti-matter?

One of the most compelling questions concerns the observation that our world and the observable universe consist of matter, as opposed to an equal amount of matter and antimatter. In other words, how did we get here? Over four decades ago, Nobel laureate Andrei Sakharov observed that "getting something from nothing" implied that nature’s fundamental forces must have violated a symmetry known as "CP" (a.k.a. Charge-Parity symmetry). While the Standard Model weak interaction satisfies this requirement in principle, the predicted CP-violating effect is too feeble to have produced the observed visible matter in the universe. Thus, a new CP-violating interaction must have been present in the early universe. The question is: what was that force and when did it make the visible matter?

The last moment when such an interaction could have done the job was roughly 10^{-11} seconds after the Big Bang, when the universe was still much hotter than it is today. While it is impossible to recreate those conditions directly in the laboratory, experimentalists can probe for CP-violating forces that would have been active then by searching for a property of nucleons, nuclei, and atoms known as a permanent electric dipole moment, or "EDM". In the laboratory, one tests for an EDM by subjecting a particle to an electric field, which causes the particle to precess (spin and wobble) around the electric field (see Fig. II-15). Reversing the direction of time reverses the precession direction. However the electric field does not change its direction if time is reversed (since it comes from a distribution of charges). Consequently the precession does not change direction, and this violates time-reversal symmetry. This violation of time-reversal symmetry then leads to the CP violation discussed above.

The first experiment to look for this property of the neutron was carried out in the 1950’s by Nobel laureate Norman Ramsey and collaborators. Since then, searches have also been performed on neutral atoms, molecules, and the muon. While there has yet to be an observation of a non-zero EDM in any system, the level of sensitivity has improved dramatically, resulting in nearly ten orders of magnitude more sensitivity compared to the original Ramsey experiment. The null results imply that any CP-violating effects in the Standard Model strong interaction are extraordinarily small, leading to the idea of a new symmetry associated with a hypothetical particle called the axion that could make up part of the non-luminous "dark matter" in the cosmos.

Today, nuclear scientists are poised to carry out experiments 100 times more sensitive, providing access to energy scales beyond that available at the LHC. The current focus is the neutron, where a U.S.-led experiment is being developed for the Fundamental Neutron Physics Beamline at the Oak Ridge Spallation Neutron Source. This beamline was completed in 2010 with funding from the DOE ONP to utilize "ultracold neutrons" (UCNs), whose typical velocities are below 10 m/s (in contrast to neutrons at room temperature that have velocities of around 2.2 km/s). The experiment represents a major shift in the quest for a neutron EDM. Though other searches are being mounted in Europe, Japan, and Canada, the U.S. approach is anticipated to have the highest sensitivity and will benefit from improvements in neutron sources.

In parallel with this flagship experiment, U.S. nuclear scientists are utilizing neutral atoms. Further improvements for the highly sensitive mercury experiment are in the works, while a new effort to observe the EDM of a radioactive radium isotope, in which the EDM is enhanced due to its pear-like shape, using atom trapping techniques is underway at Argonne National Lab. U.S. nuclear scientists are also leading an effort with radioactive radon atoms at the TRIUMF laboratory in Canada. These latter experiments would benefit from high intensities of radioactive species afforded by FRIB. Looking further to the future, an R&D effort is underway on a proton EDM search using a storage ring that would possibly be mounted at Brookhaven National Laboratory.

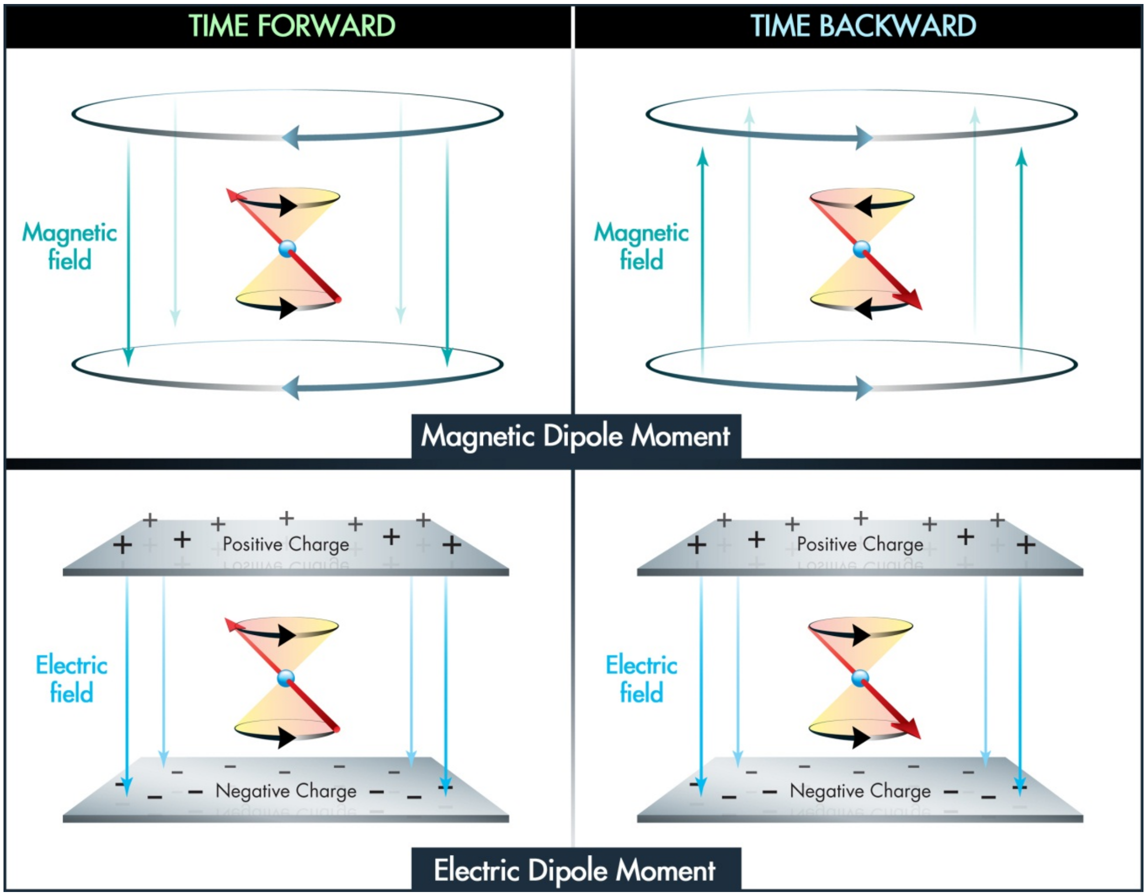


Figure II-15. The top panels illustrate the precession or wobble of a particle's magnetic dipole moment, assumed to be pointing in the direction of the particle's internal spin, in the presence of a magnetic field for time running forward (left) and backward (right). Since the backward picture correctly depicts the "movie running backwards in time" it respects time symmetry. The situation is quite different for an electric dipole moment shown in the bottom two panels. Since the electric field is produced from static charges, compared to the magnetic field from moving charges, it is unchanged for time reversal and the precession is also unchanged. This failure to "run backwards in time" shows that the presence of a non-zero electric dipole moment violates time symmetry.

The observation of a non-zero EDM in any of these searches would constitute a major discovery with significant implications for the origin of visible matter and the nature of new forces in the early universe. 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. Extensive theoretical work is needed to predict how various candidates for the "new Standard Model" might give rise to EDMs in different particles, 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 non-equilibrium environments in the early Universe. The prospects are exciting.

What is the nature of neutrinos and how do they influence the evolution of the universe?

In the quest to understand the laws of nature, knowledge of the fundamental forces and fundamental particles, quarks and leptons, is necessary. Neutrinos are leptons that carry no electrical charge, interact only via the weak force, and remain the least understood of the fundamental particles. We have observed that there are three distinct types or flavors of neutrinos, which pair with their charged lepton partners: the electron, muon, and tauon. However, we have found that neutrinos of a given flavor are actually comprised of a superposition of three neutrino states characterized by a distinct mass value (see Fig. II-16). This discovery was made by observing that neutrinos created via weak interaction processes transform to different neutrinos of different flavor as they propagate through space, a phenomenon known as neutrino oscillations. Such behavior is not accommodated within the original Standard Model where neutrinos are assumed to be massless.

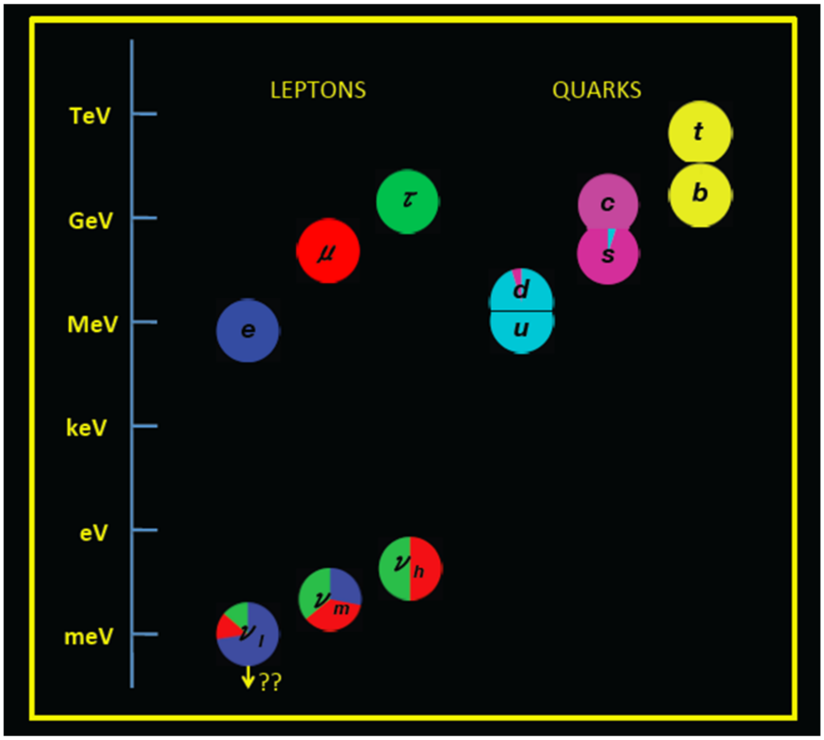


Figure II-16. The masses of quarks and leptons. The neutrinos, labeled, ν_l, ν_m, and ν_h (for light, medium and heavy) represent neutrinos with well defined mass states that correspondingly can be considered as a mixture of flavor neutrinos states ν_e (blue), ν_μ (red), and ν_τ (green). The absolute value and ordering of the neutrino masses is not yet known.

These transformations can be described with three new mixing parameters that characterize the composition of the neutrino flavors. Two of these mixing parameters are known from measurements of neutrinos produced in the atmosphere, the sun, accelerators, and reactors. In the past year, the third parameter has been determined for the first time by three different international experimental efforts located near reactors in China, France, and Korea. The most precise measurement was carried out at the Daya Bay reactor complex in China, where U.S. nuclear scientists joined their Chinese colleagues to observe neutrino oscillations using detectors located 350-2000 m from power reactors. The observed value of the mixing parameter offers good prospects for future experiments to search for symmetry violations in weak interactions.

The discovery that neutrinos are not massless has been transformative in another way—it means that a neutrino could have an astonishing property of being its own anti-particle! An extremely rare nuclear decay mode known as neutrinoless double beta decay offers the only viable experimental method to test for this possibility. This process occurs when an atomic nucleus decays radioactively by emitting two electrons (or two positrons), in contrast to ordinary radioactive decays in which one or more neutrinos emerge as well. The observation of this most exotic decay mode would provide irrefutable evidence that neutrinos are their own anti-particle and correspondingly that the symmetry of lepton number conservation is violated. As such, the search for this mode is both a fundamental symmetry test and a probe of the nature of the neutrino. Its observation would also provide strong experimental guidance for theories that go beyond the Standard Model, yielding insights into the origin of neutrino mass. In particular, if neutrinos are their own antiparticles, they could not gain their mass through the interactions with Higgs particles in the same way as all other elementary particles in the Standard Model. Neutrinos with this property could also be key players in generating the excess of matter over anti-matter as discussed above, where in this case the asymmetry could arise in the early universe from an excess of leptons over antileptons.

Numerous national review committees, both in nuclear and high energy physics, have emphasized the importance of undertaking a new series of experiments with increased sensitivity to neutrinoless double beta decay. The experimental task is extremely daunting as the experiments are probing decay half-lives on the order of 10^{26} to 10^{28} years (by comparison the age of the universe is only ~ 10^{10} years). These experiments require unprecedented purity of materials in order to reduce potential backgrounds from naturally occurring radioisotopes that could obscure or mimic the signal. Based on the extreme experimental challenges, measurements using a variety of experimental techniques in various nuclei where this decay mode might occur are needed.

U.S. scientists are involved in several major efforts, employing four different nuclear isotopes (germanium-76, telurium-130, xenon-136, and neodymium-150) with total detector masses ranging from 30-200 kg. Two of these efforts are being led by U.S. groups and mounted within the U.S. The MAJORANA DEMONSTRATOR uses enriched germanium-76 and is being constructed at the Sanford Underground Research Facility in South Dakota. EXO-200, an enriched xenon-136 experiment, is collecting data at the Waste Isolation Pilot Plant (WIPP) in New Mexico. This year EXO-200 reported the first observation in xenon-136 of an allowed decay known as two neutrino double beta decay while showing that the half-life for the neutrinoless decay mode must be greater than 1.6×10^{25} years, i.e., 10^{15} times greater than the age of the universe. Three other experiments with significant participation by U.S. nuclear scientists are underway. One known as

KamLAND Zen is based in Japan and has recently confirmed the EXO-200 results, another CUORE is constructing a novel telurium-130 based experiment at an underground laboratory in Italy, while SNO+ in Canada is transforming the original Sudbury Neutrino Observatory to a neodymium-150 based double beta decay experiment.

To reach sensitivities to a half-life beyond 10^{26} years, and to probe increasingly smaller neutrino masses will require much larger, tonne scale, experiments with backgrounds reduced to incredibly low levels, less than or equal to a single background count per tonne of material per year under the neutrinoless double beta decay signal, which is about 50-100 times lower than what has been achieved in previous experiments. If the current generation of experiments successfully demonstrate such low backgrounds, then a major future priority for U.S. nuclear science will be to proceed building at least one tonne scale experiment.

In addition to the tantalizing possibility that neutrinos are their own antiparticles, we have not yet determined their absolute masses. This knowledge has important implications for understanding large-scale structure of the universe and the origin of mass. The most sensitive experiments to directly measure the mass of neutrinos utilize nuclear beta-decay of nuclei. Such studies have not yet been able to determine the mass, but have shown that neutrinos must be at least 250,000 times lighter than the electron. The reason for this large difference is not known, though models beyond the Standard Model that unify forces at much higher energies, the so-called Planck scale, predict that if neutrinos are their own anti-particles, such light masses are indeed expected.

An experiment currently under construction, known as the Karlsruhe Tritium Neutrino experiment or KATRIN, aims to determine the absolute neutrino mass. An international effort with significant participation by U.S. nuclear scientists, KATRIN measures the beta decay of tritium, an unstable heavy isotope of hydrogen. When operational in 2014-2015, KATRIN will improve limits obtained from the best direct measurements to date by tenfold. It will be important to compare the direct beta decay results, which are model independent, with neutrino masses determined from cosmology and astrophysics observations, which rely on a number of model dependent parameters. A discrepancy would likely force a reevaluation of cosmological models. Should the neutrino masses be so small that KATRIN only sets an upper limit, there is a possibility that a novel measurement technique recently proposed by U.S. groups could ultimately reach sensitivities ten times better than KATRIN which may be sufficient to establish the neutrino’s mass.

It is also worth noting that if neutrinoless double beta decay is observed, it offers a sensitive, albeit model dependent, probe of neutrino mass. Extracting the mass from the observed half-life requires reliable theoretical calculations related to the similarity of the nuclear structure properties of the nuclei involved in the decay process. Such calculations are underway.

Looking Deep Inside the Sun with Neutrinos

In the past decade, experiments deep underground have been directly observing the Sun, not by looking at its light, but by observing neutrinos created during fusion of protons deep in the Sun’s interior. The primary motivation for these experiments was to explain the "solar neutrino problem"—the observation by Nobel laureate Ray Davis that the Sun appears to produce only a third of the neutrinos predicted from nuclear fusion. A series of experiments, Borexino, SNO, and SuperK, all with significant U.S. participation, provided definitive proof that the Sun is actually producing the expected number of neutrinos, but that two thirds of these neutrinos have transformed to other neutrino flavors by the time they are detected at the Earth. This provided compelling evidence that neutrinos oscillate as discussed above. Solar neutrino experiments continue to provide improved data on neutrino mixing properties.

In addition to the primary proton-proton fusion process that powers our Sun, there is another process known as the Carbon-Nitrogen-Oxygen or CNO cycle. This cycle is thought to be the dominant fusion process in heavier stars, but should contribute less than 10% of the Sun’s energy generation. Several experiments, including the SNO+ experiment being constructed in Canada, Borexino at Gran Sasso in Italy, and the proposed LENS experiment in the U.S. aim to observe neutrinos from the CNO cycle. These measurements combined with improved studies of the weak interactions in deuterium will provide a better understanding of nuclear fusion processes powering the Sun.

Precision Tests—Uncovering Footprints of New Forces

Precision measurements using muons, electrons, nucleons, pions, and nuclei (see the bottom two boxes in Table II-1) search for tiny deviations from the Standard Model predictions. Much like footprints left by the fleeting appearance of something now unseen, these could indicate the existence of additional forces that might address puzzles remaining in the Standard Model. Such forces would be associated with new subatomic particles; these could, in principle, be produced at the LHC, though in some cases their properties might make detection impractical. Taken together, information obtained from precision tests and high-energy accelerators yields a more complete window on possible new laws of nature than either one alone. Hence, the pursuit of nuclear physics precision tests constitutes an important component in the quest to discover nature’s basic interactions.

At present, one of the strongest indications from precision searches for new forces beyond the Standard Model comes from the result of an experiment known as the muon g-2 experiment. The experiment measures the muon’s magnetic moment, an intrinsic quantum mechanical property that is precisely predicted by theory. When compared with the current theoretical prediction for the Standard Model expectation, the result from the Brookhaven E821 experiment led by U.S. nuclear scientists indicates a difference of roughly 3.5 standard deviations, a strong hint that something is amiss. (Typically such discrepancies are not considered "discoveries" unless the deviation is at least 5 standard deviations.) Possible explanations include new "supersymmetric" forces or interactions arising from a very light particle that behaves analogously to the photon. The latter possibility provides additional motivation for dedicated "dark photon" searches at Jefferson Lab, as described below. A next phase for the muon g-2 experiment, again under the leadership of U.S. nuclear scientists, is planned at Fermilab starting in 2016, aiming at a factor-of-four improvement in experimental precision. Coupled with refined Standard Model predictions, results from this next generation measurement could yield either an even more significant deviation from Standard Model predictions—providing incontrovertible evidence for new interactions—or agreement with the Standard Model, thereby producing one of its most impressive successes.

A similarly powerful low-energy probe of new forces relies on the scattering of electrons from targets containing hydrogen or nuclei. The electrons can be polarized, with the relative orientation of their spin and momentum being either parallel or anti-parallel. Any difference in the scattering rate for the two different orientations signals a violation of parity symmetry, known to be a good symmetry in all but the weak interaction. Thus, precise studies of parity-violating electron scattering, or PVES, provide a window on possible new weak interaction-like forces. The first in this generation was carried out at SLAC in the last decade using polarized electron-electron, or "Møller" scattering. A next generation measurement, the MOLLER experiment, is proposed for the 12 GeV program at Jefferson Lab. The anticipated precision would complement studies at SLAC and LEP but at much lower energies. Comparison of the results will test a key feature of the Standard Model, namely, the energy-dependence of the weak mixing angle, which describes the degree to which primordial force carriers in the early universe have "mixed" to become the photon and Z-boson in today's cosmos. A deviation from the Standard Model could signal new interactions associated with new super-massive particles that might have existed in the early universe. Should evidence for new forces and particles be discovered at the energy frontier at the LHC, such deviations could help discriminate between competing theoretical explanations. In other scenarios, searches for such deviations explore theoretical models in which LHC sensitivity is very small or absent. Measurements of PVES with proton or nuclear targets provide similarly powerful but complementary probes of new forces between electrons and quarks. Measurement on a proton target, the Q-weak experiment, recently completed data taking with the 6 GeV beam at Jefferson Lab. With completion of the 12 GeV energy upgrade at CEBAF, a new detector called SoLID would measure inelastic electron-deuteron scattering with high precision to search for new weak interactions as well as novel features of quark-quark and quark-gluon interactions within the Standard Model.

Both the PVES and muon g-2 studies focus on processes where there is no net change in the electric charge of the lepton (electron or muon) or quarks involved. In contrast, radioactive decays, such as the decay of the neutron to a proton, electron, and anti-neutrino, require a change in quark charges and the presence of leptons with differing charges. Studies of these processes have now reached a level of sensitivity comparable to that of the PVES experiments and complementary to what is accessible at the LHC. Unlike the accelerator scale PVES and muon g-2 efforts, studies of radioactive decays entail a broader array of smaller scale but exquisitely precise studies. In particular, a comparison of the decay rate for the charged pion to a positron-neutrino pair with that for a positive muon and neutrino provides a uniquely sensitive probe of possible new electron-quark interactions that would be mediated by spinless particles. New measurements of this comparison with better than part-per-thousand precision are being carried out at the TRIUMF laboratory in Canada and the Paul Scherrer Institute in Switzerland, with U.S. nuclear scientists leading the latter effort.

Within the U.S., a dedicated program of neutron decay studies is underway that utilizes both cold and ultracold neutrons. The "UCNA" collaboration at Los Alamos National Laboratory has recently completed one of the world’s most precise determinations of the parity-violating β-particle asymmetry. Together with the neutron lifetime, the result provides important input for a test of another key feature of the Standard Model that predicts how quarks of different species mix. A deviation from this property could indicate the existence of additional, heavy quarks and leptons, new weak interactions that have complementary parity properties to the Standard Model weak interaction, supersymmetric particle effects, or other new interactions. An improved measurement of the neutron lifetime at the National Institute of Standards and Technology is poised to make the world's best "in-beam" based determination, while a new ultracold neutron trap technique is under development at Los Alamos National Laboratory. Looking to the future, measurements of additional neutron decay parameters will be carried out by the "Nab" collaboration at the Fundamental Neutron Physics Beamline at the Oak Ridge Spallation Neutron Source. Neutron decay measurements will also complement the precision study of radioactive nuclear decays that continues as a powerful means of searching for new interactions.

Looking for New Particles Beyond the Standard Model

Historically, the search for new particles has been in the purview of particle physics. However, these searches now benefit from technology, expertise and facilities in nuclear science. In some cases equipment built by nuclear scientists (e.g., neutrinoless double beta decay) can also be used to search for new particles. Thus nuclear scientists are actively engaged in many such searches, with the results being of broad interdisciplinary interest.

Astronomical and cosmological observations indicate that fully 95% of our universe is composed of non-visible matter or energy. Ultimately any new Standard Model must incorporate the nature of this dark matter and dark energy. Terrestrial direct searches for dark matter utilize the fact that dark matter in our galaxy should occasionally collide with atomic nuclei and produce a characteristic signature. In the U.S, direct detection dark matter experiments are funded by high energy physics (DOE) and particle astrophysics (NSF), however nuclear scientists are involved since both the nuclear scattering signal and the backgrounds are dominated by nuclear physics processes. Searches are also underway to look for "dark photons" that might be associated with the dark matter. Such "dark photons" would mediate a postulated attractive interaction between dark matter particles, analogous to the photon-mediated Coulomb force between electrons and the atomic nucleus. Planned searches include APEX at Jefferson Lab Hall A, the Heavy Photon Search, at Jefferson Lab Hall B (HEP), and the proposed DarkLight experiment at the Jefferson Lab Free Electron Laser (FEL). Likewise, postulated "sterile" neutrinos that do not interact via the weak force might exist and be observable in the disappearance (rather than oscillation) of neutrinos as they propagate through space. Such neutrinos would be a clear signal of new physics with important implications for cosmology and astrophysics. Several new laboratory-based searches for the existence of sterile neutrinos are being developed by nuclear scientists.

Summary

The nuclear physics sub-field of fundamental symmetries and neutrinos is a vibrant and continually evolving effort, answering key questions about fundamental interactions among particles, and the evolution of our universe.

There have been major advances since the 2007 Nuclear Physics Long Range plan, with new science, new experiments, and new facilities. The recommendation concerning the establishment of an underground laboratory has been realized, although not exactly as originally envisioned. The decision of the National Science Foundation not to pursue a Deep Underground Science and Engineering Laboratory was unexpected. However, supported by a combination of state, federal and private funds, the Sanford Underground Research Facility (SURF) has begun operation at the 4850’ level in the Homestake mine in Lead, SD. This new facility, described in the facility section of this report, provides the deepest underground laboratory space in the U.S. Although at a shallower depth than envisioned for DUSEL, SURF is hosting an initial science program that includes several DOE Office of Science supported experiments, one of which is a search for neutrinoless double beta decay (MAJORANA DEMONSTRATOR).

This sub-field is in the midst of a major transformation. The revolutionary results of the past decade point to the limitations of the existing Standard Model of sub-atomic interactions and the need for new experiments and new theory. Excited by the intriguing questions and intellectual challenges, the field attracts a wealth of bright young researchers and universities in the U.S. are actively hiring in this area. Many of the next generation experiments are evolving from demonstration scale efforts to larger, technically complex, innovative experiments.

This is a crucial and exciting time, with rapid worldwide activities and progress. If the U.S. is to remain a leader, additional new investments by the nuclear science funding agencies will be necessary over the next 5-10 years aimed at realizing the program outlined in Table II-1. These investments include construction of at least one tonne scale neutrinoless double beta decay detector, construction of a high sensitivity neutron EDM experiment, construction of detectors for the PVES program at Jefferson Lab as well as investment in the muon g-2 experiment. These are the highest priority experiments for the field and represent a significant part of "… the targeted program of experiments to investigate neutrino properties and fundamental symmetries" discussed in the 2007 Nuclear Physics Long Range Plan.

F. Nuclear Theory and Computational Nuclear Physics

Introduction

Nuclear theory in the past decade has engendered an unprecedented level of excitement and scientific breadth impacting many areas of physics. Nuclear theory and computational nuclear physics work hand in hand with experimental efforts to make progress in nuclear physics. Nuclear theory and high performance computing provide the rationale for new experiments and give meaning to experimental data. Nuclear theorists work on every aspect of nuclear physics—on the distribution of quarks and gluons within a nucleon, or nucleons within a nucleus, on the forging of heavy nuclei in a supernova explosion or heavy ion collision, as well as their dissolution into a quark gluon plasma, on rare decays of the nucleus or tiny symmetry violating properties of matter, and on nuclear physics issues related to societal applications. Yet despite this diversity of interests, nuclear theorists share a common language and method, a mathematical and analytical approach to describe nature in terms of simple principles that allow one to make conjectures and quantitative predictions about new phenomena yet to be discovered. In fact, nuclear theorists share a common language with theorists in all other branches of physics, and the exchange of ideas between nuclear, condensed matter, atomic, high energy, and string theorists has been unprecedented in the past decade and has enriched all of the different fields.

While the analytical "pen and paper" approach of theorists remains tremendously powerful for a wide range of problems, it can sometimes be limited when trying to understand the properties of systems of strongly interacting quarks or nucleons or nuclei. In this context, computational nuclear physics provides the 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: within the core of a nucleon, neutron star or nuclear fission reactor, for example; or the turbulent birth of a supernova, or in the heart of an inertial confinement fusion reactor. As with nuclear theory, computational nuclear physics operates in an environment where ideas and methods are exchanged between different fields of physics. Many of the theory and computational highlights since 2007 span what have typically been thought of as widely disparate fields.

In the paragraphs below we highlight theoretical accomplishments in different subfields of nuclear physics. This is a selection designed to illustrate the breadth and depth of the impact of nuclear theory and computational nuclear theory over the past five years and into the next five. Certainly some important accomplishments will not be recognized for years to come. These examples show that nuclear theory and computational nuclear physics are vibrant fields with significant impact across nuclear physics and beyond.

Fundamental Symmetries and Neutrinos: the Standard Model and Beyond

A number of features of our universe, including the predominance of matter over anti-matter and the observation of neutrino oscillations, firmly establish that new and unknown physics exists outside of the framework of the Standard Model of fundamental interactions. Nuclear physics plays a central role in exploring the Standard Model and beyond by using the electroweak interaction to investigate both subatomic particle structure and astrophysical phenomena, and in looking for "beyond the Standard Model" physics through high-sensitivity tests of deviations from Standard Model predictions that complement ongoing energy frontier explorations at the LHC in Europe. Nuclear theory plays an essential role in this program, in elucidating the implications of nuclear physics tests of fundamental symmetries and neutrino properties as well as in guiding the development of the experimental program. Since 2007, substantial progress has been made in both respects.

One of the deepest questions being addressed by our field is the origin of the visible matter of the universe, which requires the violation of fundamental symmetries, such as C (charge conjugation, a reflection symmetry between matter and antimatter) and CP (C followed by a parity inversion, a reflection in a mirror). CP symmetry violation has been seen at very small levels in a few systems, but not at a level that could explain the matter-antimatter asymmetry of the universe. So the search is on for a smoking gun that could explain how our world (made of matter) came to exist. CP violation could manifest itself as small, nonzero electric dipole moments (EDMs, see discussion of Fig. II-15) of the neutron, atoms, molecules, and nuclei. Nuclear theorists have shown how present and prospective EDM searches are constraining CP-violation and their implications for the origin of matter. This involves complex calculations for EDM predictions from various candidate theories beyond the Standard Model, such as supersymmetry, as well as similarly sophisticated computations of their effects in the early universe. As a result of recent work, it is now known that the next generation of EDM searches could conclusively test the most widely considered supersymmetric scenarios for the matter-antimatter asymmetry. In this way sensitive, low energy experiments in the U.S. will complement the searches at the energy frontier.

Precision measurements of other particle properties, such as the muon anomalous magnetic moment (called "g-2"), parity-violating asymmetries in polarized electron scattering, and nuclear and neutron β-decay properties, can uncover tiny deviations from Standard Model predictions arising from new interactions. At present, the experimental result for the muon g-2 gives the most significant deviation, possibly pointing to supersymmetry, "dark photons," or other exotic new forces. As a result, nuclear theorists confronted the Standard Model prediction to extraordinary accuracy, relying both on analytical techniques as well as lattice QCD computations—a sophisticated technique to simulate quantum chromodynamics (QCD), the fundamental theory of quarks and gluons. Nuclear theorists are also achieving significant refinements in computations of quantum effects in parity violating electron-proton scattering and pion decays, rendering these studies more sensitive to new physics discoveries.

In light of these advances, in conjunction with parallel analyses of high-energy collider physics, the role of nuclear theory has taken on heightened importance in the search for physics beyond the Standard Model. For example, the observation of anomalies in the distributions of top quarks and W bosons produced in high energy proton-antiproton collisions at the Tevatron in Fermilab could point to a new particle, light "Z-prime boson" that does not couple to leptons. It has recently been shown that such a new particle could lead to new contributions to the amount of parity violation in polarized electron-deuteron scattering experiments at Jefferson Lab, or a future electron-ion collider (EIC). Nuclear theorists have also shown how combinations of tests of the unitarity of the Cabibbo-Kobayashi-Maskawa quark flavor mixing matrix (the subject of the 2008 Nobel Prize in Physics), combined with studies of pion decays into muons and electrons, could provide a novel probe of supersymmetric models, complementing what may be learned from the LHC.

Looking to the future, nuclear theory is providing important guidance to the development of the experimental program. Refinements of Standard Model predictions and analyses of possible theories beyond the Standard Model set new benchmarks for the level of experimental sensitivity needed. The progress has led to new ideas for important experiments as well, such as the proposal to search for charged lepton flavor violations at an EIC—a suggestion which was not on the horizon just five years ago but which is now a significant part of the portfolio of prospective EIC electroweak physics studies.

Electroweak tests and neutrino studies provide insights into what lies within the Standard Model as well as beyond. It has been known for some time, for example, that neutrino-neutrino interactions could play an important role in core-collapse supernovae. While incredibly weakly interacting, neutrinos are produced so copiously in this environment that they behave like a dense gas, and multiple neutrino-neutrino interactions become important to its evolution. In parallel with the numerical work, nuclear theorists have applied many-body tools to the problem, and new features of this dense neutrino gas are still being discovered, the only known many-body system in nature driven by weak interactions and exhibiting collective behavior only previously seen in strongly interacting systems of particles.

Phases of QCD and Heavy Ion Physics

QCD is the accepted fundamental theory of the strong interaction, and understanding the phases of matter that it describes is a central quest for nuclear theory and computational nuclear physics. The pressure that drives the explosion of a little droplet of quark-gluon plasma produced in a heavy ion collision, the internal friction that saps the strength of these "little bangs" and, ultimately, the phase transition in quark-gluon plasma with varying excess of quarks over antiquarks, are primary objects of study at RHIC and the LHC. The theory effort is vital to all aspects of this science program, characterizing the properties of quark-gluon matter and the dynamics of heavy ion collisions.

Rapid progress has occurred just in the last few years in the numerical calculations of the hydrodynamics of exploding droplets of liquid quark-gluon plasma. The most important microscopic input to these calculations is the determination of the pressure as a function of the energy density, and here lattice QCD has played a key role. By discretizing space and time into a grid of lattice points and then computing the thermal and quantum fluctuations of the quarks and gluons at those points directly from the fundamental laws of QCD, these supercomputer calculations now provide reliable determinations of the pressure of quark-gluon plasma. They have demonstrated that when the plasma contains as many antiquarks as quarks there is a rapid but continuous crossover from strongly-interacting quark-gluon plasma to the hadronic phase that exists at lower temperatures. Rapid advances during the past few years have allowed lattice methods to reach the precision needed to accurately describe this rapid crossover. Many theorists working on lattice QCD are focused on the problem of simulating matter with more quarks than anti-quarks, and progress has been made in exploring numerically the nature of the transition under such conditions, conditions that will be explored experimentally as an important part of the future RHIC experimental program (see Fig. II-5). Studying QCD with an imbalance of quarks versus antiquarks is a very difficult computational problem and is receiving much attention; achieving a breakthrough in lattice QCD methods to speed up such computations in the next few years is a major goal among theorists, and such a breakthrough could be expected to have wide repercussions in other fields, such as condensed matter physics, where similar computational challenges are encountered when trying to study high temperature superconductivity.

The "AdS/CFT (anti de Sitter/conformal field theory) correspondence" developed by string theorists has recently emerged as a powerful approach because it enables reliable calculations addressing the dynamics of plasmas, including their response to probes, in QCD-like theories where these plasmas are infinitely strongly coupled. Conventional analytic techniques cannot be applied to the strong coupling regime, and present lattice QCD methods cannot address dynamics. The AdS/CFT techniques, in which dynamic questions at the strong coupling level are mapped precisely onto answerable questions in a corresponding gravitational description, led nuclear theorists to a fundamental prediction for a limiting value of the ratio of shear viscosity to entropy density. This story continues to develop with experimental results coupled with relativistic viscous hydrodynamic simulations showing that the quark-gluon plasma produced at RHIC and at the LHC is a "nearly perfect liquid" (see Fig. II-7). Recently AdS/CFT has been used to demonstrate how a "QCD-like" theory can equilibrate very quickly, making the not-quite-so-rapid approach to equilibrium in heavy-ion collisions less puzzling. Relativistic heavy- ion theory (RHI) has also recently advanced to the point of describing the initial fluctuations in the quark-gluon liquid and their observable signatures in heavy-ion collisions. In the coming years, theorists can synthesize these advances together with new approaches to analyzing equilibration to solidify our understanding of how the hydrodynamic expansion of the liquid begins, to what degree the hot liquid erases memory of the initial fluctuations, and how best to use new data to quantify our knowledge of the properties of the liquid and of the initial fluctuations. Further applications of AdS/CFT pioneered by nuclear theorists have spread to atomic physics and condensed matter theory. These studies are a clear demonstration of how nuclear theory can have a wide impact across many physics disciplines.

Other recent advances in RHI theory include the application of the theory of anomalies from quantum field theory to the quantum fluctuations that make parity violating domains in quark-gluon plasma and that are similar to the fluctuations at much higher temperatures that may have played a role in creating a universe with more matter than antimatter; and advances in understanding the novel phenomenology of high gluon densities and coherent scattering in collisions between large nuclei at very high energies. RHIC is an ideal testing ground for such theories since its unique kinematic coverage allows us to probe both the coherent and incoherent regimes. Theoretical advances on these fronts will come in concert with anticipated new data.

The phenomenology of energetic particles, jets and heavy quarks has been a highlight of the RHIC heavy ion program. Jet production and modification in the environment of strongly-interacting nuclear matter, dubbed "jet quenching," is a new frontier for perturbative QCD and a thrust area for high-energy nuclear physics. It interfaces heavy-ion theory with modern developments in particle theory, such as soft collinear effective field theory. AdS/CFT calculations also play a role. Theoretical calculations will enable the experimental measurements to provide critical insights into the transport and response properties of quark-gluon plasma. Advances are being made in understanding the phenomenon of "color screening" and the dissociation of bound states made from a heavy quark and antiquark, as well as how isolated heavy quarks are swept along by liquid quark-gluon plasma.

Hadronic Physics

The last decade has seen tremendous growth in the development of precise experimental and theoretical tools to reveal how the interactions between quarks and gluons result in the measured properties of hadrons, where the term "hadron" refers to any composite particle participating in strong interactions. Nuclear theory investigations of quarks and gluons within hadrons, the regime of "cold QCD", are essential components of the 12 GeV CEBAF Upgrade science program. The main elements of this program include a complete three-dimensional tomography of the proton and experiments probing the full spectrum of strongly-interacting particles as predicted by QCD. Lattice QCD calculations at nearly zero temperature can predict the properties of special mesons (see Fig. II-1) in which the glue holding a quark and anti-quark together is vibrating like a rubber band, exotic new particles whose discovery is one of the goals of the GlueX experiment at the 12 GeV CEBAF Upgrade. Theoretical developments have allowed nuclear scientists to characterize the internal structure of the nucleon, and to formulate experiments designed to reveal this structure. Lattice calculations of distributions of quarks and gluons will provide a more complete three-dimensional tomography of the nucleon than could the experimental program alone.

Lattice QCD now provides an excellent description of much of the hadronic spectra, from the lightest mesons to excited baryon resonances. This is a remarkable achievement. QCD is a strongly-coupled theory where the masses of the constituents of the light mesons and baryons are nearly zero, and the vast majority of the mass is generated "from nothing" by the interactions themselves. Modern calculations can now reproduce this spectrum at the 1% level through improved algorithms, analytical methods, and access to large computational facilities. A new and better understanding of effective field theories that describe the low energy and momentum properties of hadrons, and the marriage to lattice QCD, have created a reliable approach to comparing QCD to nature. Since 2007, attention has shifted to the entire spectrum of hadrons, including unstable states and excitations expected in the quark model, as well as more exotic resonances with quantum numbers not appearing in the valence quark sector. Computing this rich spectrum of particles is a difficult undertaking, due to the fact the most such states can decay, but great progress is being made, and the computational effort complements the experimental GlueX program.

Understanding how the successful low-energy models of nuclear physics based on interacting nucleons emerge from QCD is an exciting, and mostly unfinished, story with nuclear theory and computational nuclear physics working hand-in-hand. Going beyond the single particle spectrum, lattice QCD studies are now just beginning to reveal the interactions between nucleons and the properties of the lightest nuclei and hypernuclei in an unphysical world with heavy quarks. It is now only a matter of time and resources before these studies are replicated for more physical quark, and pion, masses, and can begin to give information directly from QCD about phenomena that are experimentally inaccessible, such as the nature of interactions between three neutrons. This information is critical for future advances in the understanding of both nuclear structure and neutron stars, and cannot be reliably obtained in any other way. With adequate funding, great future progress can be expected in this area of computational nuclear theory.

Physics of Nuclei and Nucleonic Matter

An understanding of the properties of atomic nuclei and their reactions is essential for a complete nuclear theory, including an explanation of element formation and the properties of stars, and for present and future energy, defense, and security applications. This requires a coherent picture across many energy scales, all the way from the interactions between nucleons to the extremely deformed shapes heavy nuclei achieve as they fission into lighter fragments. At the shortest distance scale, the nucleon-nucleon interaction is governed by the underlying forces between quarks and gluons. Currently, the parameters characterizing nucleon-nucleon interactions are primarily determined from experiment. However, as discussed above, lattice QCD calculations will be particularly useful for those parts of the interactions that are difficult to address experimentally, such as the forces encountered by three nucleons approaching each other closely.

The physics of light nuclei can be studied directly with nuclear interactions and associated currents by using large-scale computing and *ab-initio* approaches that solve for nuclear structure and reactions directly from the underlying nuclear interactions. These simulations evaluate the quantum evolution of neutrons and protons at low energy similar to the way lattice QCD studies the evolution of quarks and gluons.

Within the past few years it has become possible to directly study excited states in light nuclei that resemble clusters of alpha particles, such as the low-lying excited "Hoyle" state in carbon-12. This state is essential for our existence as it governs the nucleosynthesis of carbon in stars. Important progress has also been made in relating structure of nuclei to their decays and reactions, allowing all those features to be computed simultaneously from nuclear interactions. Recent examples include analysis of scattering in light nuclei, providing crucial input for experimental fusion studies; computation of the long lifetime of carbon-14, used in radiocarbon dating; and determining the mass-radius relation for neutron stars (see Fig. II-14). *Ab initio* methods are now reaching into the realm of medium-mass nuclei like oxygen and calcium, and are starting to probe the properties of the very neutron-rich isotopes.

The celebrated nuclear shell model (or configuration interaction method), in which the complex nucleus containing many protons and neutrons is approximated by a small number in interacting nucleons, can be used to make detailed studies of nuclear structure in limited regions of the nuclear chart. Calculations of nuclear properties and reactions in *ab-initio* and configuration interaction approaches are critical not only for an understanding of nuclei, but are increasingly important for interpreting nuclear experiments probing physics beyond the Standard Model and understanding the role of nuclear dynamics in astrophysics.

For larger nuclei and fission, density functional theory plays a critical role. It describes the properties of nuclei in terms of the neutron and proton distributions inside the nucleus. This theory is directly tied to experimental data and to *ab initio* theories of neutron-rich nuclei and inhomogeneous neutron matter. Modern nuclear density functional theory provides an excellent characterization of global nuclear properties including binding energies, radii, and shapes. Density functional theory is also being used to address the dynamics of fission, the structure of nuclear states with extreme angular momenta, and superheavy nuclei at the extremes of mass and charge.

The roadmap for this area, shown in Fig. II-17, involves the extension of *ab initio* and configuration interaction approaches all the way to medium-heavy nuclei, and the quest for a universal interaction in the nuclear density functional theory that will allow description of all nuclei up to the heaviest elements. The direct coupling from nucleon-nucleon interaction scales (~100 MeV) to nuclear binding scales (~1-10 MeV) to collective excitation scales (<1 MeV), facilitated by effective field theory, provides a coherent picture of the structure and dynamics of all nuclei as nucleonic matter found in astrophysical environments, including neutron stars and supernovae. To realize this vision, the properties of rare isotopes are an essential guide. For example, they will help constrain the poorly known, but crucial, interactions that depend on the neutron-to-proton imbalance, elucidate the role played by three-nucleon forces, and quantify the impact of low-lying decaying and scattering states on the structure of weakly bound nuclei. The Facility for Rare Isotope Beams (FRIB) will be essential for gaining access to key regions of the nuclear chart where the measured nuclear properties will challenge established concepts and highlight shortcomings and required modifications to current theory.

The coupling between *ab initio* and density functional theories has also been critical addressing related problems extending beyond nuclear physics. Nuclear theorists have provided some of the most accurate calculations of the zero- and finite-temperature properties of a "unitary" gas of cold Fermi atoms and applied their nuclear methods to nano-scale superconducting metallic grains.

Nuclear Astrophysics

A major accomplishment of 20th century nuclear physics was to relate virtually all astrophysical phenomena to microscopic nuclear physics. In the past five years, new developments in nuclear astrophysics in the observational, theoretical, and computational areas, have been dramatic. Observationally, the recent discovery of a nearly two-solar-mass neutron star, combined with extraction of the mass/radius relationship from astrophysical observations, have placed very severe restrictions on the equation of state of cold and dense hadronic matter. These observations are quite consistent with microscopic theories of the nuclear equation of state, and are beginning to yield detailed information on the difference between properties of nuclear matter with equal numbers of neutrons and protons and pure neutron matter. Observations of neutron star cooling are also transforming the field, providing evidence for the onset of neutron superfluidity. Anticipated observations of gravitational waves from neutron star mergers and unique data on very neutron-rich nuclei from FRIB can yield much more information, potentially further constraining the equation of state of dense hadronic matter.

Nuclear theory and computational physics, coupled to experiment and observations, are playing increasingly key roles in nuclear astrophysics. Computational developments have also been dramatic, fundamentally altering our picture of core-collapse supernovae. During the past five years, studies of these supernovae in three spatial dimensions have emerged to supersede the previous more limited capabilities in two dimensions. These improved calculations are radically transforming our views of the importance of instabilities and turbulence to the explosion mechanism, as well as of their character, yielding insights not available previously. New codes have also enabled realistic whole-star models of thermonuclear supernova explosions (Type Ia's), including the deflagration-to-detonation transition. The first detailed multi-dimensional stellar evolution calculations have also been published, going well beyond traditional spherical models that employed *ad hoc* convection theory. New physics issues, including coherent neutrino oscillations, are being addressed, with the potential to have an important impact on both the microphysics (e.g., the neutrino hierarchy) and the macroscopic physics (e.g., the nucleosynthesis) of core-collapse supernovae. Recently, the first neutron-star merger simulations in full general relativity with magnetic fields have been completed and it appears possible that these mergers could play a significant role in the synthesis of the heaviest elements.

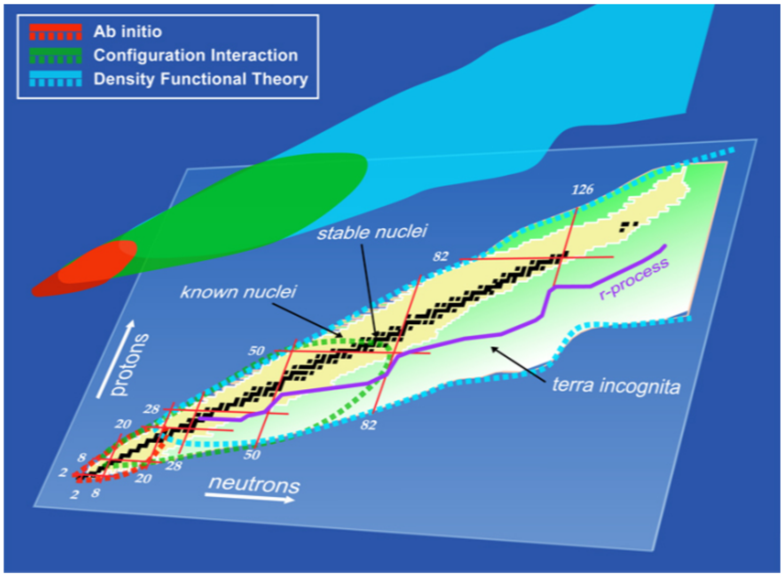


Figure II-17. The colored bands at the top indicate domains of major theoretical approaches to the comprehensive description of the structure of complex nuclei. By investigating the intersections between these theoretical strategies, one aims at developing a unified description of the nucleus.

Computational Nuclear Physics

Computational nuclear physics has been central in all subfields of nuclear physics, including: lattice QCD studies of hadrons and quark-gluon plasma; physics of fundamental symmetries; studies of nuclei and nucleonic matter; mechanism of neutron star mergers and supernovae; and various societal applications (see Fig. II-18). Computational nuclear physics in the U.S. has had a big impact because this field has historically led in both people and resources.

People remain the key factor. In particular, early-career scientists working at the interface between nuclear theory, computer science, and applied mathematics are critical to make future impact, especially in the era of extreme computing that demands the novel coding paradigms and algorithmic developments required by novel architectures. Successful career models for scientists at the interface of nuclear physics and computer science are essential, as is support for scientists at the student and postdoctoral level. The SciDAC DOE program has been critical in this regard, coupling diverse efforts to achieve maximum impact.

High-performance computing provides answers to questions that neither experiment nor analytic theory can address, and, hence, it becomes the third leg supporting the field of nuclear physics. Both personnel and computational facilities are required to enable and ensure this vision. Unfortunately, the U.S. leadership position in computational nuclear physics is endangered by the substantial investments made in other countries. For example, Japan has now allocated approximately 4 times the computational resources to nuclear physics than is available in the U.S.

Teaching and Mentoring

Teaching and mentoring is a core activity in nuclear theory and computational nuclear physics. Summer schools are critical in both acquainting students with the breadth of the field (as in the National Nuclear Physics Summer School) and in providing advanced training in more focused schools, for example with the TALENT initiative and the Lattice QCD summer schools. The future of nuclear physics generally is endangered without a vibrant nuclear theory program, and training and mentoring of students and postdocs is the key.

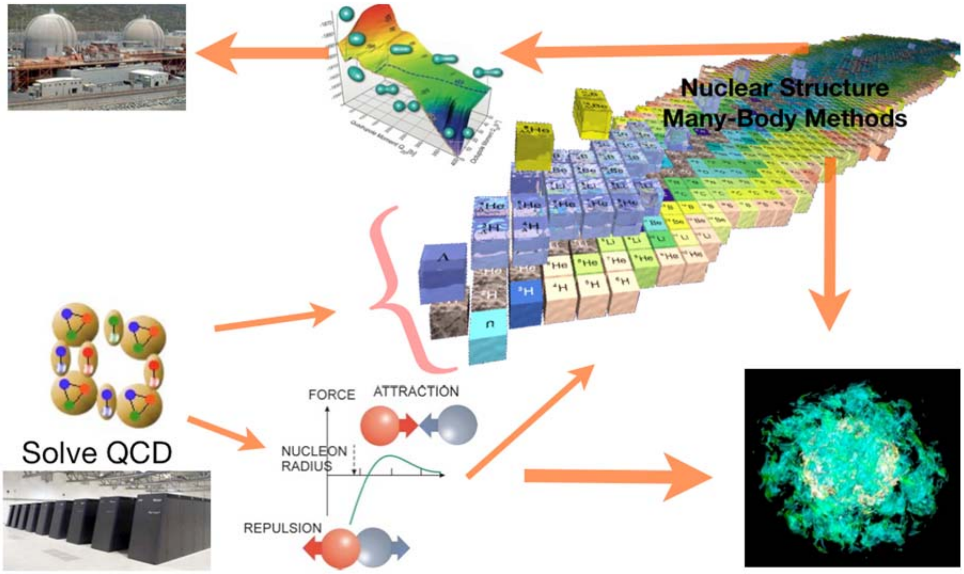


Figure II-18. Unification of nuclear theory through high performance computing (courtesy of Martin Savage). Nuclear theory addresses the nuclear interaction from lattice QCD, and ties these interactions to nuclear structure and dynamics providing an understanding of the physics of nuclei and advancing applications, including nuclear reactors and our understanding of supernovae and other astrophysical environments.

A Thriving Nuclear Theory Effort is Critical to the Field

Theory and experiment typically leapfrog over each other, each taking turns advancing science. Virtually none of the current major experimental initiatives in nuclear physics could have been conceived of without prior fundamental advances in nuclear theory. Nuclear theory is unquestionably at the heart of our field, and nuclear physics in the U.S. will remain healthy only if the theory and computational physics programs are sustained. So what does this require?

Nuclear theory is carried out by relatively small groups at universities and at national laboratories. It is closely coupled with experimental programs and it employs a variety of computational tools, including the nation’s top computational facilities at national labs. These small groups form a strong intellectual community, nationally and internationally. The Institute for Nuclear

Theory (INT) in Seattle, its European analogue ECT* in Trento, Italy, the Physics Frontier Center JINA (Joint Institute for Nuclear Astrophysics), and large theory collaborations, including the DOE topical collaborations and SciDAC computational projects, have all helped to invigorate research in many areas of nuclear theory, have fostered interactions with theorists from neighboring research fields, and have raised the visibility of nuclear theory within the international scientific community. The INT creates a unique environment where researchers from different institutions and backgrounds meet, working closely together on critical physics issues, fostering new ideas and collaborations.

Compared to operations of major facilities, theory is inexpensive—people are the main resource in this sub-field. Small changes in the nuclear theory budget have a dramatic effect, particularly on the support of students and postdocs, who are the future of the field. When support for students and post-docs declines, the best young scientists turn away from nuclear theory and seek a more predictable future elsewhere, and nuclear physics enters a downward spiral. Since FY2011, support for theory has declined dramatically— by more than 10 percent—significantly reducing our ability to train the next generation (Fig. II-19). Support for computational physics has also declined dramatically, particularly in comparison with the rapid growth internationally. This overall decline is rapidly endangering U.S. competitiveness.

A successful program of nuclear theory *cannot be achieved with flat-flat funding* from FY2013; **a rapid return to the FY2011 funding level + cost of living curve is necessary for the continuing viability of the nuclear theory program**, which in turn is critical to the health of nuclear physics as a whole. With adequate funding, nuclear theory and computational nuclear physics can be expected in the near-term to bring breakthroughs in many aspects of nuclear physics, which greatly enhance investments in the experimental program, including understanding how quarks and gluons behave in extreme environments, determining nucleon interactions directly from QCD, creating fully realistic simulations of neutron stars and supernovae, predicting which neutron-rich elements will exist and how heavy elements will decay via fission, and producing a more complete understanding of how sensitive low energy experiments can probe new physics beyond the Standard Model, complementing measurements at the LHC.

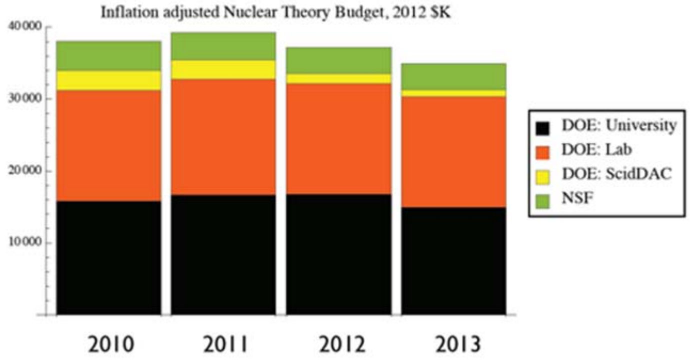


Figure II-19. Nuclear Theory and SciDAC budgets 2010-2013.

III. Facilities

Much of the experimental research in nuclear physics requires particle beams from accelerators. Today, the accelerators in use around the world primarily for nuclear science encompass a very wide range of parameters providing beams of electrons, protons, and heavy ions from a few keV (energies appropriate to nuclear reactions in stars) to many GeV (energies needed to study QCD and the high energy and high density matter of the QGP). As a result of this broad range, the size and complexity of the accelerator facilities vary enormously from small university-based ones to large international ones. Furthermore, nuclear scientists carry out experiments at facilities within the U.S. and outside the country that are not supported primarily for nuclear science research. In the U.S. these include Fermilab, where both primary proton and secondary muon and neutrino beams are utilized, and three neutron beam facilities—the Los Alamos Neutron Science Center and the Ultra-Cold Neutron source at the Los Alamos National Laboratory, the Spallation Neutron Source at Oak Ridge National Laboratory, and the NIST Center for Neutron Research at the National Institute of Standards and Technology – Gaithersburg.

Below, we provide very brief descriptions of the major facilities used by U.S. nuclear scientists. A more detailed discussion of these and other facilities is available in the recently published report from the NRC2012 report. An overview of accelerators around the world has been published by Working Group 9 of the International Union of Pure and Applied Physics and is available at http://www.triumf.info/hosted/iupap/icnp/Report41-8-2012.pdf.

A. Present and Future Large U.S. Facilities

Thomas Jefferson National Accelerator Facility

The Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility is a world-wide unique facility. Commencing operations in 1995, it was the first continuous, rather than bunched, beam recirculating linear accelerator that used superconducting radiofrequency technology. It has been operating for the past 17 years serving a large and international nuclear physics community of more than 1400 users. The wide range of beam energy and intensity, high longitudinal electron polarization, and unprecedented beam stability are a result of many significant technical innovations developed at Jefferson Lab over the lifetime of CEBAF. This has enabled a rich variety of experimental discoveries that have advanced our understanding of the strong force, the structure of hadrons including protons and neutrons, the dynamics of quarks inside hadrons, and has led to sensitive searches for physics beyond the Standard Model of particle physics.

CEBAF has completed approximately 70% of an energy upgrade that will double its maximum energy from 6 to 12 GeV. This will open new avenues of discovery both enhancing and expanding the nuclear physics opportunities there. Ten new accelerator modules will be added to the existing 40 modules in the free space at the end of each of the two linacs (see the left panel of Fig. III-1) and the magnets in the original 9 arcs will be upgraded to enable higher fields. Figure III-1 shows a schematic view of the facility and a recent aerial view of the lab indicating the progress being made on the upgrade.

The broad range of nuclear and Standard Model physics topics, enabled by the upgraded 12 GeV CEBAF, will require a variety of experimental approaches. A suite of upgraded spectrometers and detectors in Halls B and C to support the planned experimental program is being prepared. Further, a new arc provides an additional pass to deliver 12 GeV to the new experimental Hall D, where a tagged bremsstrahlung photon beam facility and solenoidal detector package called GlueX will be housed. Upgrades to the beam line and associated beam polarimetry in Hall A gives flexibility to include novel one-of-a-kind large-installation experiments. The four experimental Halls together will produce a core set of capabilities that are well matched to the demands of the experimental program described in Section II of this report.

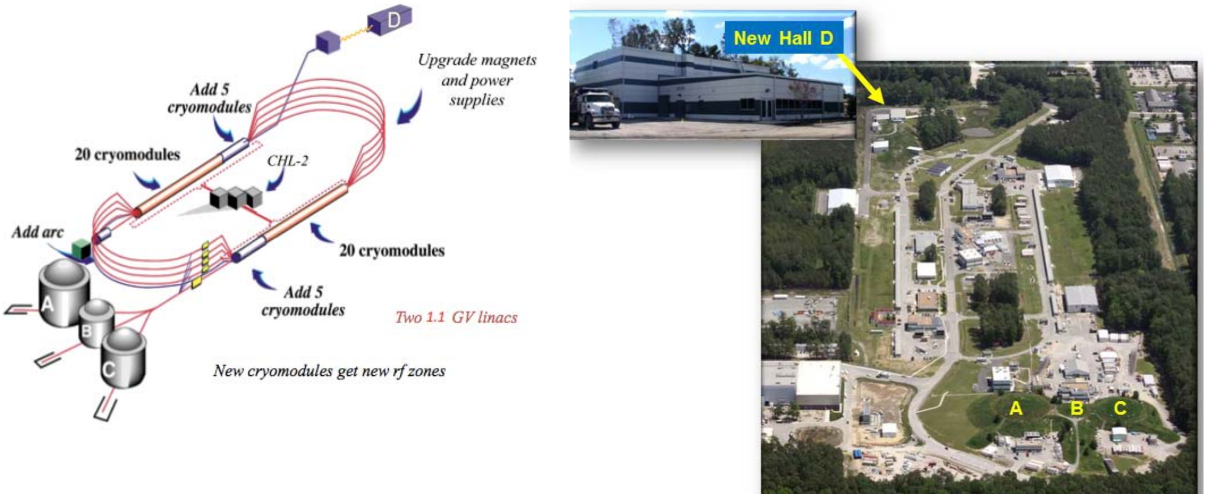


Figure III-1. Left: The main components of the CEBAF upgrade to 12 GeV. Right: Aeriel view showing the four experimental halls.

Finally, the unique capabilities of 12 GeV CEBAF, which will become available beginning in 2014, has generated considerable interest in new initiatives to search for physics beyond the Standard Model of particle physics that cannot be carried out elsewhere in the world. These initiatives, which will require new investments in detectors, will build on the experience gained in measurements carried out during the 6 GeV era.

The Relativistic Heavy Ion Collider

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the only ion-beam collider facility devoted primarily to the study of QCD (colliders have two beams of equal energy circulating in opposing directions, and are used to obtain the highest possible collision energy in the laboratory). RHIC has unprecedented capability to collide a wide array of atomic nuclei, with masses spanning the periodic table, over a wide range in energy; such versatility is required for the study of the Quark-Gluon Plasma (QGP). RHIC is the world's only polarized proton collider, providing unique insights into the fundamental question of the spin of the nucleon.

Since 2007, RHIC has made continuous and very substantial improvements to its performance. The RHIC-II Luminosity Upgrade was endorsed by the 2007 LRP and was achieved three years early and at about 10% of the cost relative to the project considered in the LRP, due to a breakthrough by RHIC R&D in bunched-beam stochastic cooling. This pioneering technology was implemented during the period 2010-12, via the successive addition of three planes of beam pickups and kickers (see Fig. III-2), which cool the beam in three dimensions. The currently achieved RHIC-II heavy ion "luminosity" (which is the rate of collisions that are usable for physics) is a factor 18 larger than the initial design specification of the RHIC machine. A final upgrade, a 56 Megahertz superconducting radiofrequency cavity scheduled for installation in 2014, will boost the RHIC-II luminosity to 20 times that of the original design.

The RHIC polarized proton luminosity has also experienced steady growth. A of factor two improvement is expected following the installation of new electron lenses in 2013, and an upgrade to the polarized ion source, also in 2013, will increase polarization by 5%. Longer term improvements currently under discussion include the installation of additional "Siberian Snakes" to improve the polarization further, as well as a large luminosity increase based on electron cooling.

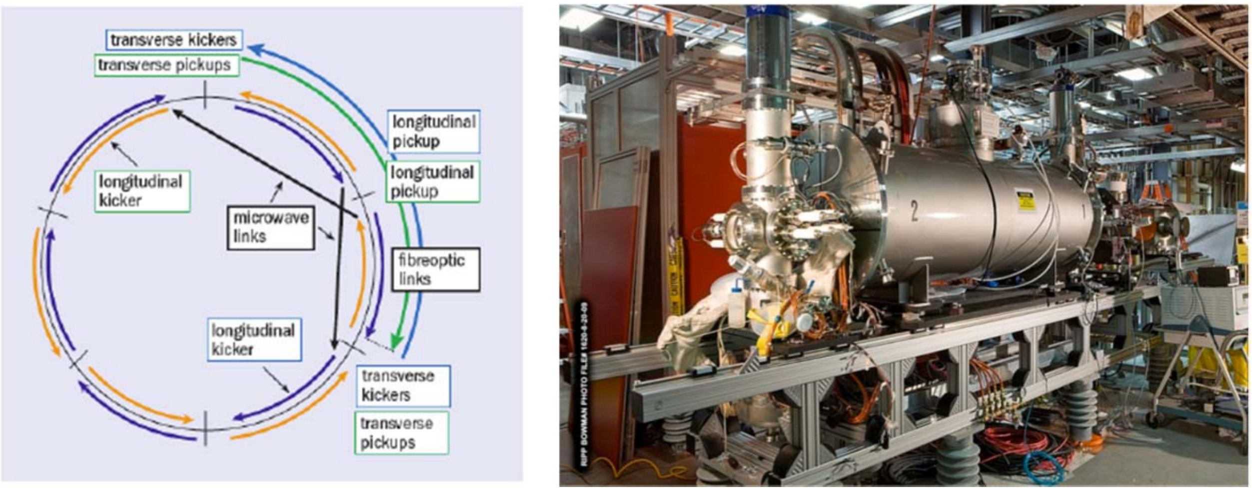


Figure III-2. Left: schematic of RHIC Stochastic Cooling System, right: recently installed EBIS ion source.

RHIC has two large experiments, PHENIX and STAR, whose designs differ significantly, giving them strengths in different physics areas. There is also substantial overlap in capabilities, which allowed many of the discoveries thus far at RHIC to be observed and confirmed by both experiments. The experiments have undertaken continuous upgrades over the lifetime of RHIC, both in their detector instrumentation and in their ability to record and analyze datasets whose size and complexity grows with the increasing luminosity of the collider.

For study of the quark-gluon plasma, the primary emphasis of RHIC running to date has been the collision of gold nuclei at top RHIC energy (equivalent to 200 GeV per proton-proton collision). However, RHIC and its experiments have also exploited the unique flexibility of the facility to study collisions of gold nuclei at lower energies, and the recorded datasets now span a factor 20 in collision energy, at nine distinct energy values, enabling a detailed mapping of experimental signatures as the quark-gluon plasma is effectively "turned off" with lowering of the energy. Colliders by their nature become less efficient (specifically, have lower luminosity) as the beam energy is decreased. Measurements at 20 GeV and below, which are crucial for the Critical Point search discussed in Section II-C, require an upgrade based on electron cooling in the RHIC ring. This will increase the luminosity in the low-energy range by a factor between 5 and 10 and will be the first implementation of three-dimensional electron cooling at a collider. This pioneering development utilizes current RHIC R&D to develop a Superconducting Radiofrequency "electron gun", which also has applications in Energy Recovery Linear Accelerators, LHC luminosity upgrades, and a future Linear Collider.

Another recent major upgrade to the RHIC facility, which was carried out jointly with NASA, is replacement in 2012 of its old ion source, the aging Brookhaven Tandem, by EBIS, the Electron Beam Ion Source, which gives RHIC significant new flexibility in choice of ion species and provides for more cost-effective operation. The 2012 RHIC run already exploited this new flexibility, with both copper-gold and uranium-uranium collisions. These choices of ion species allow the experimenter to select collisions with special, unusual geometric configurations, thereby testing the dependence of particular effects on the size and shape of the Quark-Gluon Plasma. EBIS further enables the production of polarized beams of helium-3 ions, giving new capabilities to the RHIC Spin program.

The Brookhaven Linac Isotope Producer (BLIP) is an integral part of the RHIC complex. BLIP uses the proton injector linac to produce a number of isotopes for domestic use. Very important examples are Sr-82 for cardiac imaging and Ge-68 for antibody labeling and as calibration sources for PET imaging. The use of this facility is very cost effective for the DOE Isotope Program as it is maintained and operated by some of the same staff who also operate RHIC. During routine RHIC running, BLIP can be run with only a small incremental cost for power and scientific personnel. BNL also hosts one of the annual Summer Schools in Nuclear and Radiochemistry sponsored by the American Chemical Society and is addressing the well-documented shortage of nuclear chemistry expertise in the U.S.

FRIB

The Facility for Rare Isotope Beams, FRIB, (Fig. III-3) will be the world’s most powerful radioactive beam facility, making nearly 80% of the isotopes predicted to exist for elements up to uranium, as shown in Fig. II-11. FRIB capabilities will provide unprecedented opportunities to study the origin and stability of nuclear matter and keep the U.S. community at the forefront of the field. It will be an international user facility, which will provide U.S. researchers a location to base major programs and play leading roles in equipment operation and development, and define the future directions of the field.

With the ability to explore the elemental variety of reaccelerated beams at FRIB, it will be possible to study most reactions of astrophysical importance and to carry out many different types of nuclear structure experiments. What will make FRIB unique is its use of a 200 MeV/u, 400 kW heavy-ion driver linac, whose power level, and consequent intensity and reach, is unmatched at other existing facilities, or those now under construction, around the world. FRIB will provide intense beams of rare isotopes through the in-flight fragmentation and fission of fast heavy-ion beams combined with gas stopping and reacceleration. The full complement of fast, stopped, and reaccelerated beams will be available for experiments with a broad suite of equipment. The facility includes infrastructure to support approximately 100 users on site at any given time. FRIB will be the world’s best facility for addressing key nuclear science challenges articulated in the 2007 LRP and in the NRC2012 report. Specifically the unique features of FRIB will allow the delineation of the proton or neutron limits of existence to higher masses than other facilities. It will double the number of neutron-rich nuclei that will lead to new information about matter with unusual features such as halos, skins, and their new collective modes. FRIB will provide the U.S. community with a valuable source for production of rare isotopes that are crucial for the exploration of fundamental symmetries. The accelerator's high power will yield the greatest number of different isotopes produced anywhere in the world, thereby allowing the possible r-process sites and the respective paths to be determined. It also will be the only place where measurements of most of the key nuclear reactions involved in explosive astrophysical environments can be made.

With its ability to produce a wide variety of isotopes, FRIB has the potential to make a unique contribution to the DOE isotope production program when it comes on line. Plans for harvesting important isotopes are being studied at MSU.

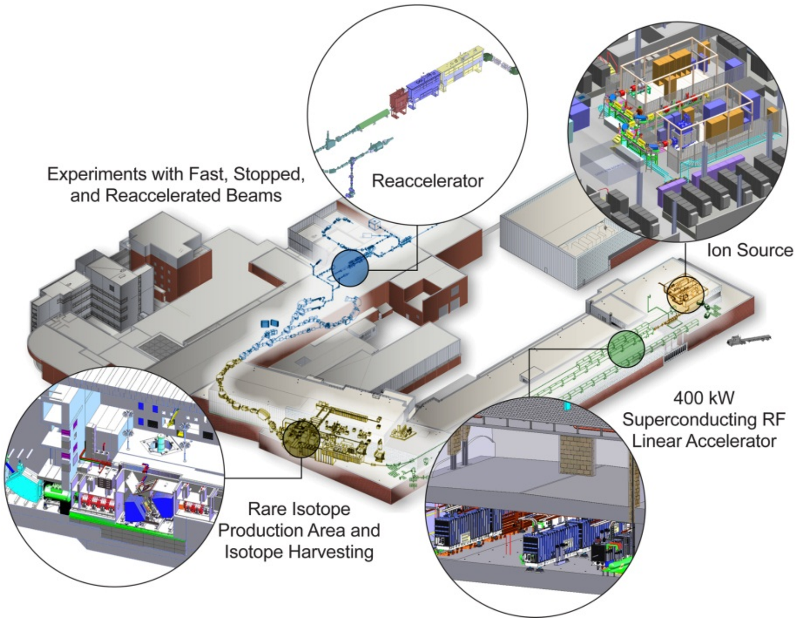


Figure III-3. Overview of the FRIB facility. Cutouts show details of the new equipment that is to be built. The existing NSCL beam lines and equipment are between the end of the new beam line following the production target and the re-accelerator area. When completed, FRIB will be the highest powered rare isotope beam facility in the world.

B. Low-Energy U.S. Facilities

There are two national user facilities operational in the U.S. for nuclear structure physics and nuclear astrophysics. These facilities are the NSF-supported National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University and the DOE-supported ATLAS superconducting linac facility at Argonne National Laboratory. These two user facilities accept research proposals from throughout the world and machine time is allocated by international program advisory committees based on scientific merit.

NSCL

The National Superconducting Cyclotron Laboratory, NSCL, is an NSF funded national user facility with a user organization of over 1200 registered members. The primary research is in the areas of nuclear structure and nuclear astrophysics using beams of rare isotopes. Rare isotopes at NSCL are produced in-flight from stable ion beams from helium up to uranium, with energies up to 160 MeV/u and beam power of up to 1 kW. As illustrated in Fig. III-4, NSCL's Coupled Cyclotron Facility (CCF) has produced over 1000 rare isotope beams and used them for research. Historically the facility has operated at between 4000 and 5000 hours per year. Modest applied programs in biology, materials studies, and radiation effects in semiconductor devices, are carried out with the beams available at the facility.

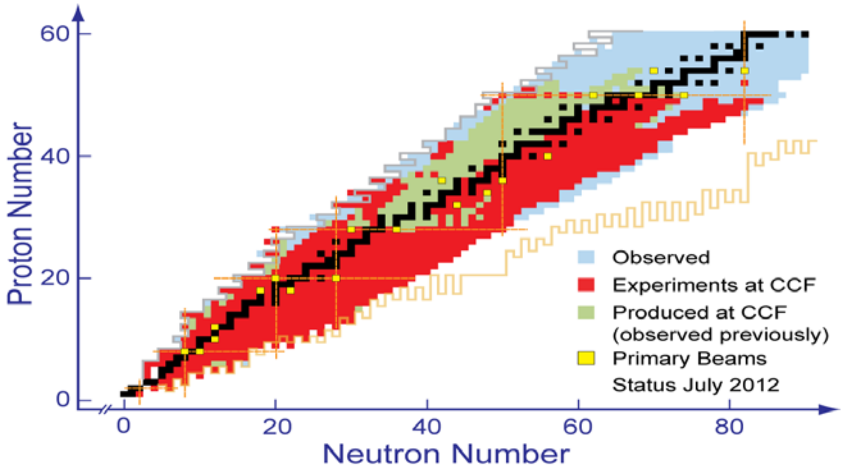


Figure III-4. Rare isotope beams produced at NSCL are shown in red and green. Over the past 10 years NSCL's Coupled Cyclotron Facility has produced more than 1000 isotopes beams for research in nuclear structure, nuclear astrophysics, and fundamental symmetries. The yellow squares show the primary beams used to produce the isotopes

A significant upgrade is underway with the addition of a 3 to 6 MeV/u post accelerator, ReA3, which will reaccelerate in-flight separated rare isotope ion beams. This facility will supply many reaccelerated beams that are not available at ISOL facilities. ReA3 will enable structure research at energies close to the Coulomb barrier, e.g., Coulomb excitation, capture or transfer reactions with new detectors developed by the user community, which cannot be done elsewhere. It also will enable a new set of experiments to determine important reaction rates for explosive stellar nucleosynthesis. An FRIB Joint Oversight Group has been formed between DOE and NSF to coordinate the transition from an NSF- to a DOE-supported national user facility.

ATLAS

The ATLAS facility at Argonne National Laboratory has the capability to accelerate intense stable beams up to energies of 20 MeV/u and to use them either directly for experiments, or to produce light to medium mass radioactive beams through nuclear reactions where a heavy nucleus strikes a light target. Due to small cross sections and focusing of the reaction products, this system is limited to the production of light radioactive nuclei close to the valley of stability. A recent addition is the CARIBU upgrade at ATLAS, which now provides neutron-rich fission fragments produced from the spontaneous fission of Californium that can be studied at low energy or following reacceleration through ATLAS.

ATLAS supports a broad research program with over 400 users from the U.S. and abroad. One focus of the future research program will be the production of heavy rare isotopes of elements heavier than uranium. Study of the heaviest nuclei can be accomplished by fusion-evaporation reactions or transfer of neutrons and protons in a process called deep inelastic reactions. In the future, ATLAS will provide an important stable beam capability that will complement the capabilities of RIB facilities in the U.S. and around the world.

University-based facilities

Presently the U.S. supports five University-based accelerator laboratories, which provide research opportunities for the nuclear structure and astrophysics community frequently not available at the national facilities. Besides operating their core research program, the laboratories educate and train a substantial number of graduated students and postdocs for the field. The accelerator facilities at Florida State University and Notre Dame are supported by NSF. The DOE supports facilities at Texas A&M University, the Triangle Universities Nuclear Laboratory (which partners programs at Duke University, North Carolina State University, and the University of North Carolina), and Lawrence Berkeley National Laboratory in conjunction with UC-Berkeley. While limited funding for these facilities prevents them from having staff sizes needed to be user facilities, they provide research opportunities through collaborative agreements between local and external researchers. In addition to the research and student training done at these smaller facilities, they often lead the development of equipment and techniques that will be employed at the larger facilities.

Recent Closures

In the last two years, two U.S. accelerator facilities have been closed, the Wright Nuclear structure Laboratory at Yale and the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge, which was operated as a user facility until early in 2012. Both closures have led to a significant drop of beam hours for the low-energy program. The loss of HRIBF in particular has seriously impacted near term radioactive beam research in the U.S.

C. U.S. Underground Facilities with Nuclear Science Activities

There are four U.S. underground facilities that are hosting underground science experiments related to nuclear science. The deepest is the Sanford Underground Research Facility (SURF) with a depth of 4160 meters water equivalent (m.w.e.) at the Homestake mine in Lead, SD. The facility, established with the support of a combination of state, federal and private funds, has been operating underground laboratories since 2011 and is currently hosting two large DOE Office of Science supported projects, including the MAJORANA DEMONSTRATOR, as well as a number of smaller scale experiments representing a variety of science and engineering disciplines. Annual operations of SURF are being supported by the DOE Office of HEP. Additional underground facilities include the Soudan Laboratory (2040 m.w.e.) in northern Minnesota, the Waste Isolation Pilot Plant (1580 m.w.e.) in New Mexico (whose main mission is to support the nation's National Transuranic (TRU) Program), and the Kimballton Underground Research Facility (KURF) (1400 m.w.e) located in the Chemical Lime Company's Kimballton Mine near Ripplemeade, Virgina which is operated by Virginia Tech University. SURF, Soudan, and WIPP utilize access via vertical shaft conveyances, while KURF provides drive in access via a ramp.

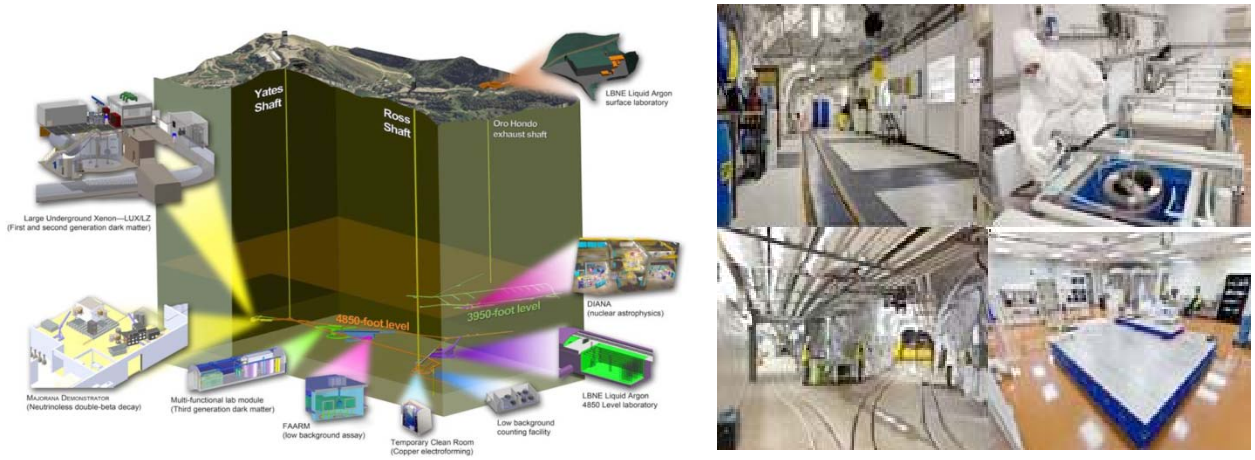


Figure III-5. Left: cross-sectional view of Sanford Underground Research Facility (SURF) at the Homestake mine in Lead, SD. Right: Views from the drifts and clean room facilities at SURF.

A collaboration of nuclear astrophysicists proposes the development of a Deep underground Ion Accelerator for Nuclear Astrophysics, DIANA, for measuring low energy reaction cross sections with cosmic ray induced gamma and neutron background being substantially reduced. The DIANA project is being considered for funding by NSF and would be located in one of these underground sites. A site selection has not been made.

D. Large International Facilities - Europe

The Large Hadron Collider

The Large Hadron Collider (LHC) at CERN (Fig. III-6, left panel) utilizes the world's highest-energy and highest-intensity proton collisions to explore electro-weak symmetry breaking and to search for particles and symmetries beyond the Standard Model. In addition, for four weeks each year the LHC collides heavy atomic nuclei, to study the Quark-Gluon Plasma and other QCD phenomena. At present the LHC collides lead nuclei at an energy equivalent to proton-proton collisions at 2.76 TeV. Following a planned long shutdown for repairs and upgrades in 2013-14, the LHC will collide lead nuclei at a proton-proton equivalent of 5.5 TeV, a factor 27 greater than RHIC top energy. The larger collision energy corresponds to larger initial temperature of the QGP of about a factor of two, and to a significantly longer lifetime of the plasma phase. In addition, the larger collision energy results in much higher production rates of energetic jets (hard-scattered quarks and gluons), photons, and massive W and Z particles, as well as copious production of heavy charm and bottom quarks, all of which play important roles in the study of the QGP.

The LHC luminosity (intensity of collisions) for heavy ion beams is considerably smaller than its luminosity for proton beams, due to physical processes generated by the very intense electromagnetic fields surrounding ultra-high energy beams of heavy nuclei. The LHC luminosity currently achieved for lead-lead collision is a factor 10 less than that achieved at RHIC for gold-gold collisions. Upgrades currently planned for 2018 will increase the LHC luminosity for collisions of heavy nuclei by about a factor 10.

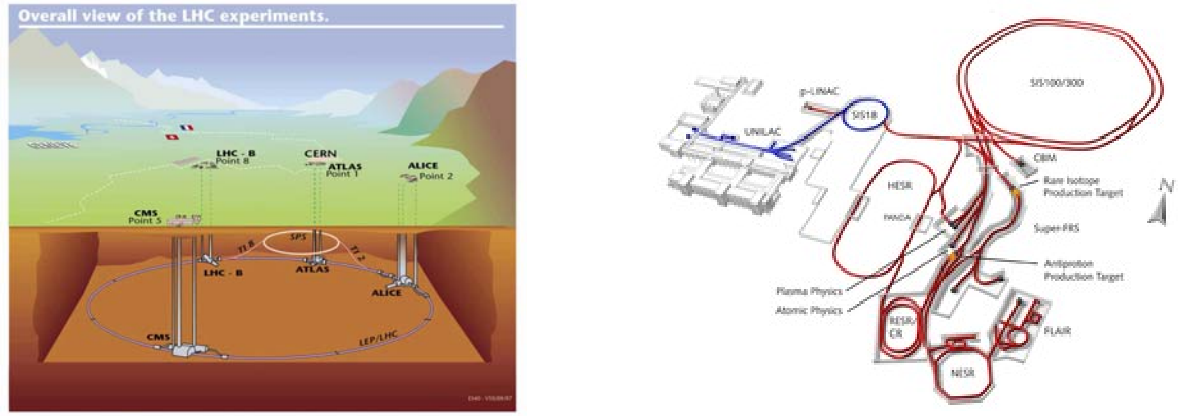


Figure III-6. Left: schematic of the LHC. Right: schematic of the FAIR facility.

The LHC has two large, general purpose detectors, ATLAS and CMS, which have broad measurement capabilities for both proton-proton and heavy ion collisions, and two more specialized detectors: ALICE, which is dedicated to study of the Quark-Gluon Plasma and is optimized for high performance for a wide variety of measurements in the complex environment of high energy nuclear collisions, and LHCb, which focuses on CP violation in the beauty-quark sector and is typically not operated during heavy ion running. There are about 100 U.S. participants in the LHC heavy-ion programs of ALICE, ATLAS and CMS, with modest U.S. capital investment. The impact of these programs is substantial.

GSI/FAIR

The present GSI facility uses particle beams up to 1 GeV/u for uranium that interact with a production target that is followed by a fragment separator to produce secondary in-flight radioactive-ion beams. The program at GSI is world-leading in the unique parts of nuclear science that require storage rings. Its upgrade, FAIR, the Facility for Anti-proton and Ion Research, will be a powerful facility. The overview of the facility as it is presently proposed is shown in the right panel of Fig. III-6. For nuclear structure and astrophysics, it will be complementary in many ways to RIBF (a facility in Japan that is discussed below) and NSCL/FRIB, due to its high beam energies (up to 45 GeV/u) and the ability to efficiently use storage rings. The radioactive beam science program at FAIR is one component of the program to be carried out there which also includes efforts in relativistic heavy-ion collisions and hadronic physics with anti-proton beams.

The FAIR facility will be based on two new synchotrons, SIS100 and SIS300, utilizing existing GSI accelerators for their injection system. SIS100, which will accelerate heavy nuclei to energies equivalent to 4.5 GeV proton-proton collisions at a collider, is currently under construction and is scheduled to begin operations in 2018. SIS300, which will be built later in phase II, will accelerate heavy nuclei to energies equivalent to 9 GeV proton-proton collisions at a collider.

High energy heavy-ion studies at FAIR are done in a "fixed-target" mode, in which an energetic beam collides with a stationary target. The energy range of heavy ion collisions accessible at FAIR overlaps the lowest range of energies achievable by the RHIC Beam Energy Scan. The "fixed-target" nature of FAIR enables much greater collision rates than are achievable at colliders, by a factor 1000 or more, allowing FAIR experiments to explore aspects of quark-gluon plasma whose signals are too rare to be studied at colliders and to search for the critical point in lower energy collisions where the excess of matter over antimatter is large. The primary experiment at FAIR for studying QCD matter and the Quark-Gluon Plasma is CBM, the Compressed Baryonic Matter experiment. While CBM can run with beams provided by SIS100, full exploitation of its physics requires completion of SIS300.

GANIL

GANIL has been carrying out a program of radioactive beam physics primarily with fragmentation beams. The facility is presently undergoing an upgrade to extend this program with the addition of a high-power ISOL facility. The driver being constructed is a linear accelerator that will deliver an intense beam of deuterons to produce neutrons that will interact with a uranium target and produce neutron-induced fission fragments. The driver will also produce heavy-ion beams up to 14.5 MeV/u for ISOL or fusion evaporation production of radioactive species. The ISOL beams will be accelerated to energies up to 20 MeV/u by an existing cyclotron at GANIL and be transported to the existing experimental areas at GANIL.

HIE ISOLDE

Starting in the late 1960's, ISOLDE at CERN pioneered the development of the isotope separator on-line (ISOL) technique to produce radioactive beams. Beams at ISOLDE are produced from reaction products that are collected following the interaction of 1.4 GeV protons from the CERN PS booster with a thick production target. The resulting ions are analyzed to produce secondary beams. The facility, which began operating in the 1980's, has undergone several upgrades. A linear accelerator was added over a decade ago to produce beams up to about 3 MeV/u. The accelerator is now being upgraded to provide accelerated beams up to 10 MeV/u. This will be accompanied by an increase of the primary proton beam intensity following accelerator upgrades at CERN to provide higher beam power to the ISOLDE targets.

PSI – Paul Scherrer Institute

PSI is a multi-mission national laboratory in Villigen, Switzerland. Among other facilities it operates a 590 MeV cyclotron capable of delivering 2 mA of proton beam. This beam is used to produce secondary beams of muons and neutrons that can be used for nuclear physics experiments studying muon or neutron properties. Collaborations with significant U.S. participation have recently presented improved results on the muon lifetime, which determines the Fermi coupling constant of the weak interactions at PSI. An on-going experiment, MuSun, is also underway with U.S. leadership that will use muon interactions to help characterize the nuclear reaction rates that take place at the center of the sun. A collaboration with significant participation from the U.S. is presently studying the feasibility of using the secondary muon beam to study the charge radius of the proton. An intense Ultra-Cold Neutron (UCN) source is also under development that will be used for studies of fundamental symmetries. This source is based on the technology developed at the Los Alamos Neutron Science Center (LANSCE) UCN facility, which is used for the UCNA experiment discussed in Section II-E.

E. Large International Facilities - Asia

JPARC

The JPARC facility in Tokai, Japan, is a large, multipurpose accelerator facility that uses a combination of linear accelerators and synchrotrons to produce high-energy, high-intensity proton beams. Proton beams with more than 500 kW of beam power at 1 GeV are used to produce spallation neutrons for a range of programs in basic and applied research. Proton beams around 3 GeV are used to produce secondary pion, muon, and kaon beams in an experimental area that focuses on hadron physics and rare decays searching for physics beyond the Standard Model. Proton beams at the maximum energy of 50 GeV are used to produce a neutrino beam for measuring neutrino properties using detectors near the beam production site and a far detector in the Kamioka mine.

RIBF

RIBF at RIKEN in Tokyo, Japan, uses a series of cyclotrons to produce particle beams up to 350 MeV/u for uranium-238. The design beam intensity of 1 particle-μA for uranium, corresponding to a beam power of 10 kW, is used to produce fast beams from fragmentation. Following the production target, a fragment mass separator system is used to provide secondary beams of over 200 MeV/u to experimental areas. Due to the need to strip electrons from the beam at each stage of acceleration, RIBF is limited in beam power, with rare-isotope rates one to two orders of magnitude below what FRIB will provide. A large number of ancillary detector and spectrometer systems have been built at RIKEN allowing the program there to carry out a broad range of research primarily for nuclear structure studies with fast and stopped beams.

LANZHOU

At Lanzhou, China, a separated sector cyclotron is used to provide beams for acceleration and storage in a synchrotron ring that can accelerate heavy ion beams up to 1 GeV/A for carbon-12 and 500 MeV/u for uranium-238. Primary beams from the synchrotron can be used for experiments. They also are used to produce radioactive beams through fragmentation that can be collected in a second storage ring at the end of a fragment separator beam line where they are cooled and accelerated. Both storage rings are equipped with internal target stations. Commissioning of the main storage ring began in 2005 and it was followed by commissioning of the second storage ring. The facility is now in operation and carrying out experiments. It is used primarily by scientists in China although some U.S. groups have participated in experiments there.

F. Other Major Facilities Around the World

ISAC at TRIUMF

An ISOL facility has been developed at TRIUMF that uses the 500 MeV proton beam from the TRIUMF cyclotron at a beam power of up to 70 kW. Secondary beams produced from proton induced reactions on thick targets are separated and then accelerated up to 10 MeV/u by a superconducting linac. The beams are then delivered to ancillary detectors and spectrometers for nuclear structure and nuclear astrophysics experiments. A facility upgrade is now underway with the construction of a high power 50 MeV electron linac. The electron beam will be used to produce photons that will interact with a uranium-238 target and produce fission fragments from photo-fission. This will increase the number of secondary beams that will be available at the facility.

MAINZ

The Mainz Microtron (MAMI), located on the campus of Johannes Gutenberg Universitat Mainz, is an electron accelerator facility that features a continuous beam with energies up to 1.5 GeV. The current accelerator is called MAMI-C following an energy upgrade, which was completed several years ago. There are active hadronic physics programs at MAMI-C pursued by three major collaborations in different experimental halls focusing on electron scattering experiments, experiments using tagged photon beams, and parity-violating electron scattering experiments. The present hadronic physics program at Mainz involves a number of new initiatives for the short- and mid-term future. Besides the experimental program at MAMI-C, the construction of a new accelerator (MESA) in the energy range of 100 - 200 MeV, devoted to parity violating electron scattering is funded and underway. It will provide precision tests of the Standard Model. Both the ongoing hadronic physics program and the future Standard Model physics program from MESA are complementary to the 12 GeV CEBAF Upgrade physics program.

G. Major Facilities in the Planning Stage

The NICA Facility

NICA, the Nuclotron based Ion Collider facility, is a broad-based facility planned to be constructed at the JINR laboratory in Dubna, Russia. NICA will provide collider beams of heavy nuclei (with masses up to gold) at energies equivalent to 11 GeV proton-proton collisions, as well as polarized proton and deuteron beams with energies up to 27 GeV and 14 GeV respectively. In addition, NICA has a fixed target program at lower collision energy, utilizing proton, deuteron, and light ion beams.

The NICA Collider is a new accelerator, which utilizes the existing Nuclotron for its injection system. It is designed to provide collisions of heavy nuclei with very high luminosity. The NICA energy range overlaps that of FAIR but is achieved in collider mode. The primary collider experiment is MPD. Upgrade of the Nuclotron and construction of the MPD experiment have been approved, but construction of the Collider itself has not yet commenced.

RISP

A new effort, the Rare Isotope Science Project, is now being developed in South Korea as part of the Science Belt in Daejon, South Korea. The plans for the accelerator facility, RAON, call for a 1 MegaWatt 70 MeV proton cyclotron for ISOL production of beams followed by a superconducting linear accelerator to produce radioactive-ion beams up to 15 MeV/u. In addition, a second superconducting linear accelerator is planned to produce beams of uranium-238 up to 200 MeV/u. Either stable or ISOL produced radioactive beams would be accelerated in the higher-energy linear accelerator. Design and costing of the components is underway.

IV. Applications

Nuclear-science generated technologies are pervasive in our present-day world. These include imaging technologies in medicine, cancer treatments, sterilization of blood and other medical items, oil-well logging, ion implantation of semiconductors, the most common type of smoke detectors, forensic analysis, monitoring cargo for contraband, and of course commercial power generation. Nuclear science also provides a host of tools for research spanning the scientific disciplines. Nuclear techniques are the gold standard for measuring the age of ancient objects, from the archeological to the cosmic time scales. Nuclear-tracer techniques are used to unravel biochemical pathways, to determine the efficiency of chemical reaction vessels, and to measure the flow of ground water. Materials scientists have used approximately 100 different radioactive isotopes, from lithium-8 to francium-213, to study the behavior of defects and impurities in metals, semiconductors, and high-temperature superconductors. Nuclear technology is used to generate low-temperature semiconductor-based thermometers and to identify (by isotope analysis) the origins of both terrestrial and extraterrestrial materials. Nuclear techniques help identify the chemical form of minerals on Mars and provide the power for the rover Curiosity.

Some applications are unexpected. Recently large neutrino detectors built for nuclear science studies of neutrino properties have been applied to determining the quantity of long-lived radioisotopes within the Earth. The KamLAND and Borexino detectors are proving the first practical tools for measuring "geoneutrinos" and are helping geoscientists understand the mechanism that preserves the Earth’s molten core. Another example of an unexpected application comes from the effort of nuclear scientists who pioneered techniques for producing large quantities of highly polarized helium-3, which has properties similar to those of a dense gas of polarized neutrons and is used extensively in experiments at Jefferson Lab. This effort led to a new imaging technique that produces images of the gas space of lungs with unprecedented resolution.

This list only scratches the surface of the uses of nuclear techniques and isotopes in modern research. It is a defensible statement that nuclear techniques taken in aggregate are, after microelectronics and computers, and perhaps lasers, the most widely used set of tools in science. In the remainder of this section we list a few of the recent real-world applications of nuclear science, as well as new tools that nuclear science has added to the toolkit used by modern-day researchers.

It has been estimated that the collective value of the products made using **accelerator technology** is more than \$500 billion per annum [Phys. Today **64**, 46 (2011)]. There are about 1000 accelerators of one form or another sold every year with a collective value exceeding \$2 billion. A large fleet of accelerators are engaged in semiconductor processing, another fleet for producing short-lived isotopes for medical imaging, another for accelerator mass spectrometry, and yet another widely distributed set for radiation therapy. A newcomer in the latter activity uses proton beams. Initially the machines used to generate the protons for this treatment modality were large and expensive to operate, too large and expensive for hospitals to employ. Importing the technical advances from nuclear science—and, equally important, the accelerator physicists trained in nuclear science—**new proton therapy machines** have been designed that are both smaller and cheaper, see Fig. IV-1.

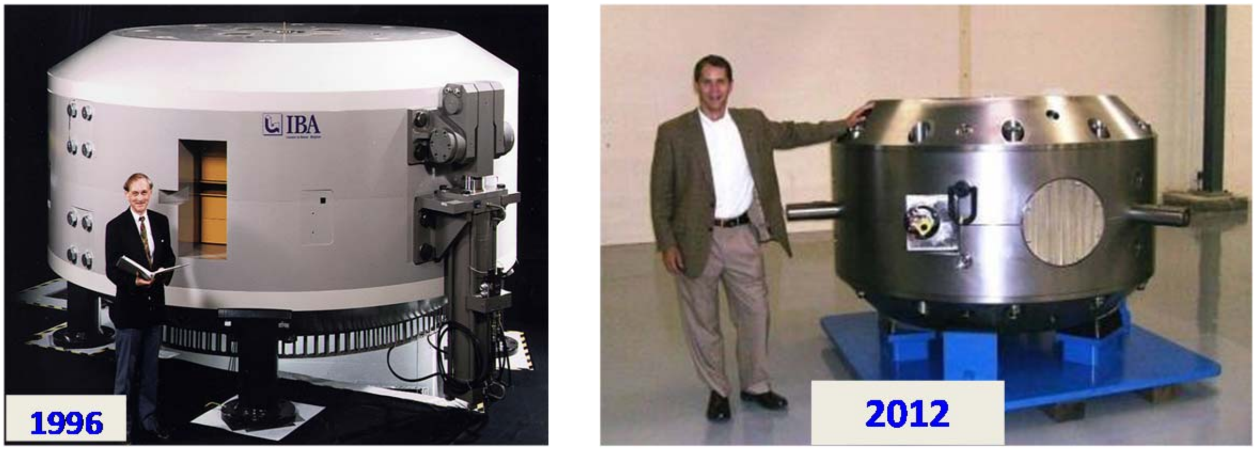


Figure IV-1. Comparison of 250 MeV proton therapy machines sold in 1996 (left) and 2012 (right). The latter, a superconducting synchrocyclotron made by MeVion Medical Systems, is small enough to be installed on a gantry system that rotates the accelerator around the patient. The new design shares some features with an isochronous superconducting cyclotron designed for neutron therapy a decade ago. Design features of the superconducting neutron and proton therapy machines can be traced to the NSCL. In this application size does matter, smaller is cheaper.

Another exciting new development in the accelerator sector, resulting from work at Jefferson Lab and RHIC at BNL, is that of the **Energy Recovery Linac** (ERL). These systems produce high-energy, high-power, and high-brightness electron beams with a very high efficiency by accelerating an electron beam in a superconducting radio-frequency cavity and then decelerating the beam, after it has been used, in the same cavity recovering almost all the energy of the beam. ERLs are well matched to applications where a powerful electron beam is needed at high energy, but where the interaction does not introduce a large energy spread, such as drivers of high-power free electron lasers (FEL) for material research. Potential applications include megawatt infrared FELs for naval defense and industrial production of ultraviolet photons for synthetic fiber processing to improve texture and thermal isolation.

Accelerator mass spectrometry (AMS) dramatically enhances the sensitivity of isotope detection and is now applied extensively in archeology, earth science, art history, biology, and pharmacology. State-of-the-art measurements of the age of ancient objects replaces the standard decay measurement of the remaining amount of a radioactive isotope present in a sample by a far more sensitive technique that explicitly counts the number of atoms of that isotope, atom by atom. As a result, there is no need to detect the decay of some of what remains to determine how much remains. Two such techniques, one using an accelerator and the other an atom trap similar to those used for studying the physics beyond the Standard Model (section II-E), are discussed below.

A new tool of this kind has been developed to study ocean circulation and the role this circulation plays in the regulation of our world’s climate. One regulation motor is the Atlantic conveyor belt system whereby warm surface water is chilled in the far North Atlantic, sinks to lower depths, and flows down the Atlantic and across the Indian Ocean to the Pacific, where it is heated, rises to the surface, and flows back to the North Atlantic, as displayed in Fig. IV-2. The entire cycle takes about 1000 years. It is becoming increasingly clear that the amount of heat transported from the tropics to the polar regions by the oceans is comparable to the amount transported by the atmosphere. Therefore, it is very important to understand this system. With a half-life of 269 years, argon-39 is particularly well suited to study questions related to ocean circulation. However, with the extremely low concentrations, argon-39/natural-argon = 8×10^{-16}, and its long half life, the decay of argon-39 cannot be measured in any reasonably sized sample. The logical separation of the decay, to indicate transpired time, from the atom-by-atom counting to determine the amount of radionuclide remaining, provides a new powerful tool.

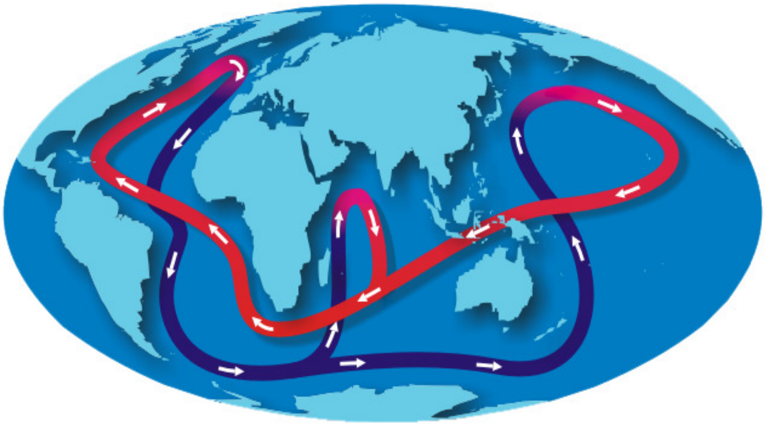


Figure IV-2. The Atlantic conveyor belt system is made up of ocean currents that transport heat from the tropics to the polar regions. Accelerator Mass Spectrometry of the radioactive isotope argon-39 will be used to explore this conveyor belt and its impact on climate. Taken from http://www.srh.noaa.gov/jetstream//ocean/circulation.htm

Like the modern application of carbon-14 dating, an accelerator is used to separate argon-39 from the far more abundant isobar (same mass number) potassium-39, the latter being 6-7 orders of magnitude more abundant. (In the case of carbon-14 dating, nitrogen-14 is the interfering background.) Measurement of isotopic ratios as small as argon-39/natural-argon = 4×10^{-17} have been achieved. This technique is now ready to be exploited to measure argon-39 concentrations in ocean water samples in order to explore the dynamics of the oceanic "conveyor belt".

The determination of the residence times and flow velocities of groundwater circulating deeply through the Earth’s crust is another challenging problem being addressed by a new nuclear tracer technique. Krypton-81, which is produced by cosmic ray-induced spallation in the atmosphere, has been identified as an ideal chronometer for determining fluid residence times on the 10^5-10^6 year time scale. A new method developed at ANL, **Atom Trap Trace Analysis** (ATTA) analyzes krypton-81 in environmental samples. With a half-life of 230,000 years and an atmospheric isotopic abundance of one part per trillion, krypton-81 can provide unique information on terrestrial processes occurring on million-year time scales. Presently this technique is being used to determine the age of the Nubian aquifer under the Sahara Desert, see Fig. IV-3. A suite of techniques like this might aid in our understanding of the time it will take to replenish underground reservoirs depleted by human activity. ATTA has been supported by grants from the DOE ONP through Applications of Nuclear Science and Technology.

The use of **radiotracers in medicine** aids in both diagnosis and treatment of many diseases. There are about **17 million nuclear medicine procedures in the U.S. annually** [J. Nucl. Med 52:24S-28S (2011)] and it has been estimated that nearly one quarter of the persons admitted to U.S. hospitals undergoes at least one diagnostic or therapeutic medical procedure using radioisotopes. For example, fluorine-18-fluorodeoxyglucose (F-18-FDG) is used to produce **2.5 million images every year in the U.S.** The application of this radionuclide relies on the fact that the cancer cells typically take up more sugar than the surrounding tissue. Thus the accumulation of

FDG as visualized by positron emission tomography (PET) informs the physician on the location and extent of disease. Just recently a research application of PET has localized regions of the brain with reduced blood flow after chemotherapy. The associated reduced brain activity has been linked with the usually temporary cognition difficulty that often accompanies chemotherapy.

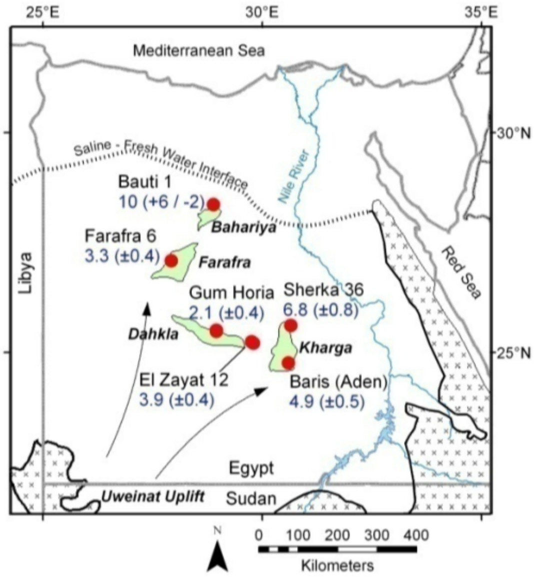


Figure IV-3 Understanding the flow of groundwater that circulates through the Earth's crust is an open question in geology. In a collaboration of nuclear and geo scientists, the precision technique of atom-trap analysis was used to measure the radioactive isotope krypton-81 in deep wells of the Nubian Aquifer in Egypt. The map shows sample locations and their krypton-81 ages (in 100,000 years) in relation to oasis areas (shaded green). Groundwater flow in the Nubian Aquifer is toward the northeast. Adapted from Geophys. Res. Lett. 31, 2003GL019234 (2004).

A recent advance in radiation therapy marries two technologies with roots in nuclear science. A company called ViewRay has just begun installing in American hospitals machines that make use of what is called open-field nuclear magnet resonance to allow for **real-time image-guided radiation therapy**, see Fig. IV-4. The information from this special form of imaging dynamically controls collimators to ensure that the radiation is optimally guided to the tumor even as the patient breathes and swallows. This instrument is another example of an idea generated by a scientist trained in basic nuclear science who chose to work in an applied area. About 35 years ago this happened with PET. ViewRay, a company that formed only a few years ago, now employs 55 people, has raised over $80 million from the private sector, is currently installing three machines and expects to initiate installation of twice that many in the coming year.

In a curious turn of history, radiotracers, empowered by the imaging techniques advanced by medical applications, have returned to the first subject for which tracers were used—plant research. In the past few years, plant research has begun making use of specially designed PET and direct positron imaging devices. The major advance has been in the capability to study the **dynamics of metabolites**, see Fig. IV-5. Recent work has addressed the transport of hormones, plant defense response to herbivory, and the role photorespiration plays in drought response.

The tracer flourine-18 that is used in F-18-FDG can be produced by cyclotrons that are sufficiently small to be operated by medical centers. Two other isotopes that fall into this category are carbon-11 and nitrogen-13, both of which have many applications. Other isotopes are beyond the reach of the machines that the medical community can realistically operate. One of these is rubidium-82. This isotope, which can be milked from a long-lived parent strontium-82, is made at the isotope production centers BLIP at BNL and IPF at LANL and is used for cardiac imaging.

For this purpose, rubidium-82 can replace technicium-99m, an isotope that to date has been made in reactors and for which the supply has been problematic. Another isotope with high promise for **targeted radiotherapy** currently in clinical trials is actinium-225. This isotope emits an alpha-particle that will destroy cancerous cells nearby without damaging healthy surrounding tissue. It also has the attractive feature of a half-life long enough to ship from a production site to hospi-

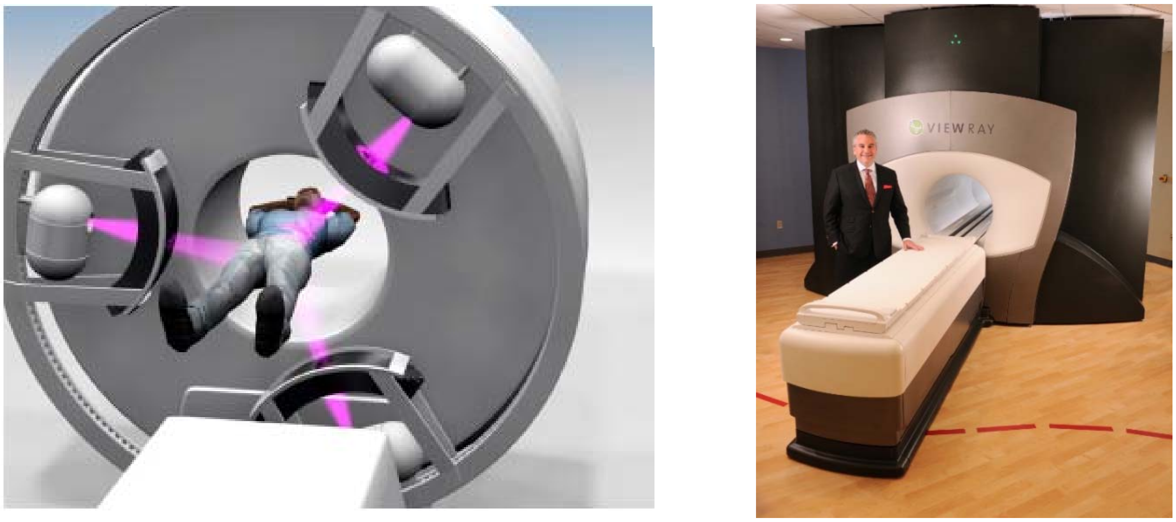


Figure IV-4. (Left) A schematic of the ViewRay machine is shown. (Right) Dr. James Dempsey, the founder and chief scientific officer of View Ray, is shown standing next to an installed imaging-therapy machine. Dr. Dempsey got his Ph.D. in nuclear chemistry studying low-energy nuclear reactions.

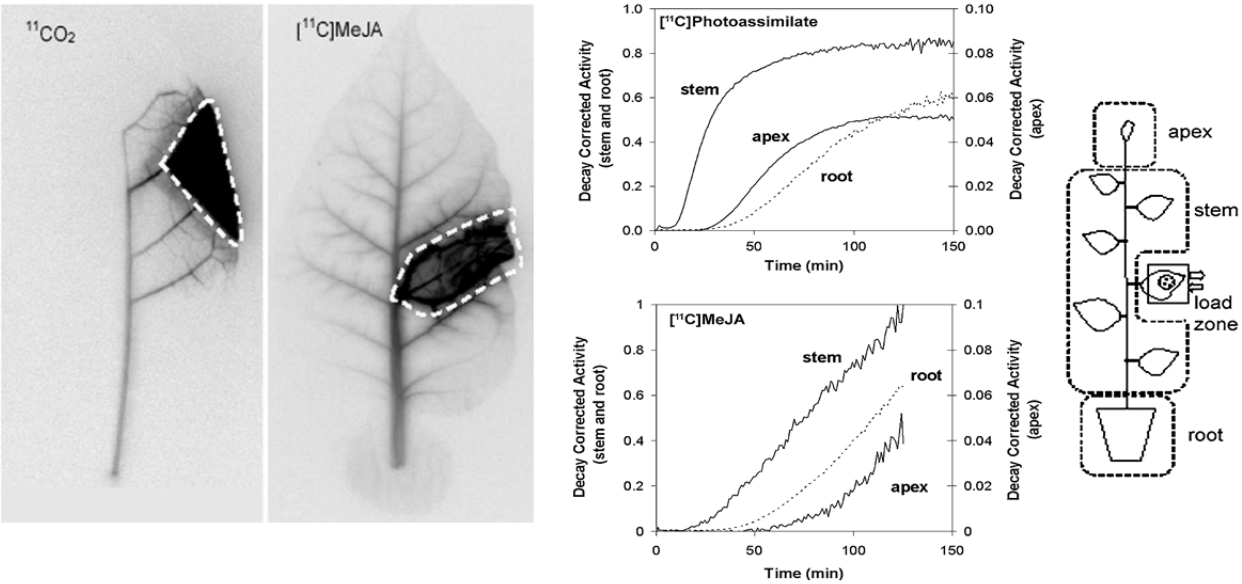


Figure IV-5. (Left) Positron autoradiographs showing distribution of carbon-11 in excised tobacco leaves 60 min after tracer administration as $^{11}CO_2$ and [carbon-11] MeJA (methyl jasmonate - a plant hormone). (Right) tracer profiles within three regions of a tobacco plant. The tracer was supplied as $^{11}CO_2$ in the top graph ([carbon-11]photoassimilate), and as [carbon-11]MeJA in the lower graph, at time zero. This work was conducted at BNL, see Planta 226:541-551(2007) and J. Chem. Ecol. 36:1058-1067 (2010). For an article related to the photorespiratory response to drought see, New Phyto., 196, 1109-1121 (2012).

tals, but short enough to be therapeutically manageable. Recently teams of researchers at ORNL, BNL, and LANL, funded by DOE Office of Science's Isotope Program in the Office of Nuclear Physics, have teamed up to improve the production capability of actinium-225. This isotope may be the first of a new treatment modality empowered by the ability of FRIB to make research quantities of terbium-149 and astitine-211, isotopes with similar nuclear properties to actinium-225 but different chemistries. This is but one example of the likely future contributions FRIB will make to the availability of nuclei, basically "**designer isotopes**" that will be of great value to society.

With these example applications in mind, the question arises whether there other isotopes with attractive combinations of physical and chemical properties that medicine has not yet made use of due to the difficulty in producing them? The answer to this question is very likely – yes. One already identified example is the pair titanium-44 → scandium-44. The extracted daughter, of this mother-daughter pair, scandium-44, can be used as an imaging agent that traces the bio-distribution of the therapeutic agent scandium-47. (The same biologically active molecule would be synthesized with either scandium-44 or scandium-47 attached and a mixture of the two delivered to the patient.) Another example is copper-67, which has been proposed as a single activity that allows for **simultaneous imaging and therapy**.

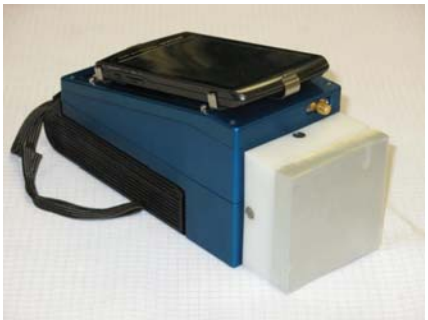


Figure IV-6. The prototype of a new type of hand-held survey meter developed by the Los Alamos National Lab that makes use of the inorganic scintillator CLYC and a pulse-shape-analysis signal-processing chip both developed for basic nuclear science research. CLYC stands for a crystal with the composition Cs_2LiYCl_6:Ce. The survey meter allows for isotope identification, directionality determination, and threat assessment.

Hand-held survey meters have become ubiquitous in modern research and industry, especially in biochemistry laboratories. The traditional design of these instruments is often adequate, however in many security situations one would like a **hand-held survey instrument capable of pointing** in the direction of the radioactivity and of discriminating between types of radiation. Such devices are now becoming available. One such example has been developed at LANL using a new detector technology—a new inorganic scintillator crystal that emits visible light when struck by radiation—and an advanced specialty CMOS chip for processing the signals from the scintillator that allows gamma rays to be distinguished from neutrons, see Fig. IV-6. While the commercial applications will be carried out independent of the DOE and the NSF, both the new crystal and the signal-processing "brains" of the device were developed for basic nuclear science applications and funded, respectively, through the DOE-SBIR and NSF-MRI programs. A parallel detector/electronics development effort at Jefferson Lab has generated improved technology for the localization and **diagnosis of breast cancer**. This technology has been patented and licensed to Dilon Diagnostics and 170 systems based on the technology are operating in clinics today. This imaging system is less expensive, and can be used in a fashion that will require a **lower patient dose,** than the alternative technologies.

Understanding the nuclear physics of fission and the decay of the fission products is essential for the control and safe operation of nuclear power reactors. While these reactors are driven by nuclear fission, about 7% of the heat produced from these reactors is from the subsequent beta decay of the ash of the fission burn rather than from the fission process itself. Even after a reactor is "shut off" (by plunging in control rods) this 7% of the reactor power remains. The fraction drops to 1% in a 2-3 hours, 0.25% in about 1 week, and decays very slowly thereafter becoming the radioactive waste problem that all are familiar with. It is this heat (at early times) that damaged three reactors and one cooling pond at Fukushima in March 2011.

Our understanding of the **beta-decay heat** between 4 and 3000 s after the fission of plutonium-239 (+n) has recently been improved by nuclear-science experiments on the beta-feeding probability of the fission isotopes technicium-102,104,105,106,107, molybdinum-105, and niobium-101. This is relevant even for reactors formally running on uranium-235, since a considerable fraction of the fission from fuel elements near the end of their life is from plutonium-239 bred by neutron capture on uranium-238. This work was initiated at ORNL and is made possible by a new technique called "trap-assisted total-absorption spectroscopy". It is not surprising that information of the beta-decay properties of fission products is a byproduct of the study of neutron-rich nuclei just shy of the rapid neutron capture nucleosynthesis (the r-process) path. Indeed the overlap of reactor physics with r-process physics is deeply connected—the decay of r-process nuclei includes beta-delayed neutron emission, and it is beta-delayed neutrons that enable control of a nuclear power reactor.

Neutron activation, which has been a powerful analytical tool for decades with some of the greatest sensitivities in all of science, has recently been given a boost by new technology. In this technique neutrons are used to generate radioactivities via the capture of neutrons on stable isotopes, which decay by emitting gamma rays with energies characteristic of the isotope created. Historically research reactors supplied the neutrons to activate samples. In the last decade, advances in small compact neutron-beam generators have made this technique portable and amenable to coarse imaging applications. These neutron beam generators are small deuteron accelerators with design features developed in recent years, primarily at the Lawrence Berkeley National Laboratory. One recent application of directed-neutron-beam activation is the study of what is behind a large 16th century Giorgio Vasari fresco. A new technique, **directed neutron activation**, is being used to test if the fresco is covering the long sought after, and incomplete, da Vinci painting of the Battle of Anghiari. Directed neutron activation is now poised to join AMS and particle induced X-ray analysis (which recently showed that the "Vinland map", which other techniques suggested was a modern forgery, could in fact be a genuine pre-Columbus map of the northeastern coast of North America) as an indispensable tool for areas of science from archeology to art history.

Nuclear physics of fission and nuclear reactions also plays a vital role in the nuclear forensics of nuclear explosions and other activities related to the production of nuclear weapons. New methods are being developed to determine the design and origin of a nuclear event (pre- and post-detonation), based on an analysis of recovered samples.

Advancing basic nuclear science has also driven **innovation in computer architectures**. The nature of lattice QCD calculations makes these computations particularly well suited for massively parallel supercomputers. This aspect of the calculations motivated a group of theoretical physicists centered at Columbia University to design a computer chip for use in special-purpose supercomputers. This chip attracted the attention of IBM computer engineers who employed aspects of the design of these chips (as well as some of the nuclear physicists in the effort) in the commercially successful Blue Gene line of computers. The application of these computers extends far beyond QCD. These supercomputers have simulated exploding stars and nuclear reactors. Climate science researchers at BNL are using a Blue Gene computer to make significant progress in understanding today's climate and how it is likely to evolve. Genomic sequencing, protein folding, predicting novel and functional phases of perovskites (materials with atomic compositions ABO_3), and brain simulations are also successful Blue Gene computational projects.

Due to the direct connection of nuclear science to societal needs, over 5% of the Office of Nuclear Physics budget is devoted to bring to maturity applications of nuclear science. The **Isotope Development and Production program** coordinates the use of facilities developed for other parts of the DOE program, as well as some dedicated isotope production facilities, to supply unique isotopes. In addition to advancing alpha-particle emitters for targeted radiotherapy and strontium-82 used for cardiac imaging, an additional example is californium-252 used for petroleum exploration. DOE also distributes stable but rare isotopes. The 2009 NSAC report "Isotopes for the Nation's Future a Long Range Plan" said, "**It is not an exaggeration to say that research and clinical studies of essential mineral nutrient metabolism in man will come to a complete halt if the support of these [stable] isotopes is curtailed**." Looking forward, **the use of separated stable isotopes in biology and medicine is likely to increase** substantially as the field of metabolomics moves out of centralized resource centers into common lab practice. This is likely to happen due to the decreasing cost of high-performance mass spectrometers with unit atomic mass resolution for large biomolecules. Once again one will find a program within the nuclear physics portfolio is essential to advance a different area of science.

Another program with a substantial applications footprint is the DOE ONP run **Nuclear Data Program**. In response to customer requests, this program provides expert analysis of nuclear data and undertakes new measurements of nuclear data where needed. Customers of this program come from a wide range of agencies and industries, including nuclear power. The web site for this world-wide resource had over 2.5 million hits in 2012. The community of nuclear scientists is sufficiently devoted to applications that the associated budget allotments have been maintained, and in fact slightly increased, even in the present financially stressed times.

In this section we have highlighted a few of the new tools nuclear science has added to the general scientific toolkit. If the past can be used as a guide, the isotopes, data, and technologies nuclear science will generate in the coming years will provide substantial new benefits to society, demonstrating once again that **nuclear science solves practical problems in our every-day lives as well as answering some of the largest questions about the nature of our universe.**

V. Nuclear Science Workforce

In the 20th century, investments in science and technology contributed significantly to economic growth and prosperity in the United States. The close connection between fundamental research in physical sciences and economic strength is well documented, for example in the recent update to the compelling 2005 National Academy of Science report "Rising Above the Gathering Storm" entitled "Rising Above the Gathering Storm, Revisited – Rapidly Approaching a Category 5". The original 2005 report stimulated an increase in federal investment. However the updated *"Gathering Storm"* report notes that while initial federal response was on the mark, various factors (including the economic meltdown of 2007-8) have weakened the resolve. The summary assessment of the report states: **"In balance, it would appear that overall the United States long-term competitiveness outlook (read jobs) has further deteriorated since the publication of the Gathering Storm report five years ago."**

A key aspect of maintaining U.S. competiveness falls directly on maintaining a sufficient Science, Technology, Engineering and Mathematics (STEM) workforce. As noted in the *Gathering Storm*: *"What must be preserved in the United States, if the nation is to compete, is an adequate supply of scientists and engineers who can perform creative, imaginative, leading-edge work—that is, who can innovate."* A similar concern is articulated in a new report from the President's Council of Advisor's on Science and Technology (PCAST) "Engage To Excel: Producing One Million Additional College Graduates With Degrees In Science, Technology, Engineering, And Mathematics"*:* **"Economic projections point to a need for approximately 1 million more STEM professionals than the U.S. will produce at the current rate over the next decade if the country is to retain its historical preeminence in science and technology. To meet this goal, the United States will need to increase the number of students who receive undergraduate STEM degrees by about 34% annually over current rates… Retaining more students in STEM majors is the lowest-cost, fastest policy option to providing the STEM professionals that the nation needs for economic and societal well-being …"** In Nuclear Science there have also been calls for an increase in the number of Ph.D.'s graduating each year. In particular, the 2004 DOE/NSF Nuclear Science Advisory Committee Subcommittee on Education recommended **"… that 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."**

The intellectual grand challenges inherent in understanding our universe draw many of the best minds in the world to the U.S. Equally importantly, they serve as powerful attractors of young people to the sciences. Research in physical sciences in general, and Nuclear Science in particular, plays a vital role in providing opportunities for Undergraduates to engage in basic research outside of the conventional classroom setting. Nuclear Science sponsors many opportunities for undergraduate research including the NSF supported Research Experience for Undergraduates (REU) program as well as targeted programs at several Historically Black Colleges and Universities (HBCU). Such opportunities have been demonstrated to improve the retention of students in STEM and are encouraged in the PCAST report. Furthermore, they prepare students for careers in hands-on problem solving, either at the Bachelor's level, or upon completing an advanced degree. Losing U.S. leadership in Nuclear Physics would have a deleterious impact on attracting young people into science careers.

In the physical sciences, large facilities are often key components in training the workforce, in addition to producing new knowledge. They provide effective outreach to their local communities, helping to nurture a high tech economy and providing key support to STEM K-12 education for both students and teachers. The educational outreach at the K-12 level, along with the role in postsecondary education are both essential to maintaining and growing the STEM workforce in the U.S. Closing a major research facility would significantly reduce the opportunity to attract and retain STEM majors. Compounding the situation is the fact that other countries are investing heavily in Nuclear Science research. Should the U.S. underinvest, future opportunities will be lost, including a variety of commercial applications.

Nuclear Science plays a key role in providing the required skilled workforce, and the U.S. has long been the world leader in this area. Fundamental research into the physics of the atomic nucleus has provided a solid foundation for technologies used in

- Nuclear medicine and health physics
- Nuclear energy
- Nuclear forensics
- Non-proliferation
- Stockpile stewardship
- Border protection and other national security challenges
- Tools, instruments, and detection techniques valued in industry and the marketplace

In many of these technologies, nuclear scientists play a unique role, as documented in a number of recent reports including: "Readiness of the U.S. Nuclear Workforce for the 21st Century Challenges" – American Physical Society 2008, "Assuring a Future U.S. Based Nuclear and Radiochemistry Expertise" – the NRC2012 report. The last of these – the decadal survey of Nuclear Physics - summarized many of these recent studies and noted: **"The 21st century has brought a growing realization that a well-trained and adequate-sized nuclear workforce is crucial in order to address the serious challenges facing our world."** while also highlighting the key elements where a nuclear workforce plays an essential role: **"The demand for a nuclear workforce for nuclear medicine, health physics, and nuclear energy is certainly not decreasing. All of these areas are important for national and world security and prosperity, yet their increasing needs come at a time when the nuclear workforce is shrinking… There are significant new requirements and challenges in the fields of nuclear forensics, border protection, and non-proliferation…" along with "… nuclear medicine for diagnosis and treatment, the handling and storage of reactor waste, the detection of the trafficking of nuclear material, nuclear forensics, nuclear weapons and stockpile stewardship, and the development of new accelerator technologies."**

All of these areas are important for U.S. security and prosperity, yet their increasing needs come at a time when the nuclear workforce is shrinking. The average age of the permanent nuclear science workforce is increasing. Scientists who began careers as faculty or national laboratory researchers in the 1950s and 1960s have retired or are nearing that milestone. Those who were students during that period are now relatively mature in their careers.

The average annual production rate over the last decade is approximately 90-95 Ph.D.'s in Nuclear Physics and 10 Ph.D.'s in Nuclear Chemistry. The production of Nuclear Physics Ph.D.'s by U.S. universities has declined by 30 percent since 1995, and about half of these degrees were awarded to foreign nationals. Many of these newly-minted Ph.D.s remain in the U.S., however they are not eligible for a number of positions in security, stockpile stewardship and threat reduction. These positions require U.S. citizens with skills in collecting and analyzing test data, developing specialized and highly sensitive detection technologies, mounting complex large scale measurements and/or simulations, and designing integrated tests for the nation¹s nuclear security complex.

In addition, national security has significant needs that require specific solutions coming from advances in nuclear physics. Accurate cross sections are needed for applications involving weapons diagnostics and performance, opening up the possibility of providing new constraints on nuclear simulations, both in the interpretation of historical Nevada Test Site data, and for forensic scenarios. In nuclear forensics, monitoring the output information, such as prompt and radiochemical signals, associated with a nuclear event (e.g., gamma, neutron, X-ray, etc.) can provide useful diagnostic information. Nuclear material measurement science has demands for detection of nuclear material that could be enabled by technological advances, such as increasing the sensitivity of nuclear particle detectors, new types of active interrogation, or non-nuclear detection modes.

As discussed above, the 2004 NSAC report on education estimated that an increase in PhD production by 20 percent is necessary if anticipated research positions in non-academic areas are to be filled. Students trained in other fields do not possess sufficiently deep knowledge of nuclear properties and the most advanced nuclear techniques to step in and fill the needs. In addition, the more general skills offered by Nuclear Science graduates include working with complex systems of hardware and software, handling Petabyte scale data sets, solving technically challenging problems in large collaborations, modeling advanced theoretical concepts, differentiating large effects from small ones, exploiting advanced mathematical techniques, and developing large-scale computer simulations. Nuclear Science graduates remain in high demand in industry, national defense, nuclear medicine, nuclear power/energy companies, and environmental applications, as well as for positions in basic research in academic and national laboratory settings. Providing the workforce needed to maintain U.S. competitiveness requires sufficient funding for graduate student support and to finance research projects upon which Ph.D. dissertations can be based.

There is a growing imbalance between the needs for growing a strong Nuclear Workforce and the likelihood of addressing these needs in the present budget environment of flat or decreasing research support. The NRC2012 report notes: **"… the workforce shortage will become acute unless a coordinated and integrated plan is implemented in order to build and sustain an appropriately sized workforce, coupled with the necessary research facilities"** A telling quote by Gordon England, Former Deputy Secretary of Defense, appears at the end of the updated *"Gathering Storm"* report: **"The greatest long-term threat to U.S. national security is not terrorists wielding a nuclear or biological weapon, but the erosion of America's place as a world leader in science and technology."**

It is clear that if Nuclear Science is to continue to provide an adequate, well-trained, workforce to the nation then continued support for basic research and the corresponding research facilities are essential. Constant dollar and constant-effort budgets do not allow the increases in Ph.D.'s required to meet projected workforce needs in nuclear science. Indeed, in such scenarios, the closure of one of the major nuclear physics experimental facilities is likely, which would have a devastating, long-term effect on the nuclear science workforce. Facilities producing high-visibility, high-impact science attract the best graduate students. The closing of one of the nation's premier nuclear science facilities will likely result in an exodus of young people from nuclear science and the ability to attract a new generation would be seriously undermined. Delays in constructing new facilities, such as FRIB, will similarly discourage adequate Ph.D. production.

Ph.D.'s in Nuclear Science

The education of PhD's in Nuclear Science between 2006 and the present time has taken place at 87 U.S. universities. These universities are located all around the country, and include both private and public institutions, as can be seen from the table below. The universities producing the highest number of Ph.D.'s generally participate in more than one subfield of Nuclear Science, and/or are located near to a major experimental facility. Almost no universities take part in all aspects of Nuclear Science, but many have programs in two or three of the areas. It is important to note, however, that about one third of U.S. universities involved in Nuclear Science have faculty in only one area. This list includes many of the nation's elite universities. Were the U.S. to lose one of the sub-fields and lose international leadership in Nuclear Science, continued Nuclear Physics research at these institutions would be in dire jeopardy.

Table V-1. Nuclear Science PhDs produced by U.S. universities from 2006 to 2012. The columns indicate the number of PhDs in each of the sub-fields of Nuclear Science: HP = Hadronic Physics, QGP = Quark-Gluon Plasma, NS/NA = Nuclear Structure, Reactions & Nuclear Astrophysics, FSN = Fundamental Symmetries & Neutrinos. Both experimental and theoretical PhDs are included in the table. RHIC Spin PhDs are included with other RHIC PhDs. The identification of subfields is based on thesis titles and abstracts and should be regarded as somewhat subjective. The data in the table is based on best-effort searches using several large PhD databases and has been cross-checked with many of the Universities, but may not be complete.

University	HP	QGP	NS/NA	FSN	Total PhDs
Air Force Inst. of Technology	1				1
Arizona State University	1				1
Caltech				7	7
Carnegie Mellon	12				12
Catholic University	1				1
CUNY		2			2
Clark University			1		1
Colorado School of Mines			9		9
Colorado State Univ.				2	2
Columbia Univ.	4	10			14
Dartmouth	1				1
Duke University	8	4	7	2	21
Florida International Univ.	9		1	1	11

Florida State Univ.	6	3	19		28
George Washington Univ.	8			2	10
Georgia State Univ.		3			3
Georgia Tech			3		3
Harvard		1		1	2
Idaho State Univ	1		3		4
Indiana University	2	3	6	11	22
Iowa State Univ.	3	3	2		8
Kent State Univ.	6	6	3		15
Michigan State Univ.		1	42		43
MIT	23	18		4	45
Mississippi State Univ.			5		5
New Mexico State Univ.	3	6			9
North Carolina State	5	1	6	7	19
Notre Dame			22		22
Ohio State Univ.	2	5	3		10
Ohio University	8	1	7		16
Oklahoma State			1		1
Old Dominion	15		1		16
Oregon State			2		2
Penn. State Univ.	1	1			2
Pittsburgh	2			2	4
Princeton		5		1	6
Purdue Univ.		5	3		8
Rice Univ.	1	1			2
Rochester		1	1		2
RPI	2			1	3
Rutgers	1		1		2
San Diego State Univ.			1		1
Southern Illinois U. Carbondale			1		1
Stony Brook Univ.		25	7	2	34
Temple Univ.	2			2	4
Texas A&M Univ.		8	15		23
Tulane				2	2
Univ. Arizona	3	2	1	2	8
Univ. California, Berkeley	1		10	9	20
Univ. California, Davis		3			3
Univ. California, Riverside		2		1	3
Univ. California, Los Angeles	3	10			13
Univ. California, San Diego			4		4
Univ. Chicago	1		1		2
Univ. Colorado, Boulder		4		1	5
Univ. Connecticut	4	2	2		8
Univ. Delaware			1		1

Univ. Houston	6	2			8
Univ. Illinois, Urbana-Champaign	10	8		9	27
Univ. Illinois, Chicago		3			3
Univ. Iowa	1		1		2
Univ. Kentucky	5		2	1	8
Univ. Maryland	8	4	1	1	14
Univ. Massachusetts, Amherst	3	1		1	5
Univ. Massachusetts, Lowell			4		4
Univ. Miami				1	1
Univ. Michigan	2		3	3	8
Univ. Minnesota		2			2
Univ. New Hampshire	4		1	1	6
Univ. New Mexico		1			1
Univ. North Carolina	2		8		10
Univ. Pennsylvania				3	3
Univ. of Virginia	14	3		5	22
Univ. South Carolina	6			4	10
Univ. of Southern California		1			1
Univ. Tennessee		2	19	2	23
Univ. Texas, Austin		2		3	5
Univ. Utah	1				1
Univ. Washington	6	7	4	15	32
Univ. Wisconsin	1	1	2	6	10
Vanderbilt Univ.		2	3	1	6
Virginia Tech				1	1
Washington U. St. Louis		4	5	1	10
Wayne State Univ.		5			5
Western Michigan Univ.			4		4
William & Mary	14			2	16
Yale Univ.		9	13	2	24
sum	223	193	261	122	799
fraction	0.28	0.24	0.33	0.15	

Between 2006 and now, over 100 Ph.D.s were granted each year for experimental or theoretical research primarily with support from DOE or NSF. Graduate students, who basically are scientists in an early stage of their careers, play key roles in all aspects of the research enterprise led by their advisors. They learn to develop new experimental or theoretical techniques, mount experiments or complex calculations, deal with large-scale computations and/or very large data sets, analyze and interpret data and results, and disseminate their results and insights in written and oral presentations to a variety of audiences. This mix of skills, coupled with specific knowledge about nuclear physics and chemistry, makes Nuclear Science Ph.D.'s a vital component of the U.S. workforce. The different subfields within Nuclear Science contribute 27%, 24%, 33%, and 16% for medium energy physics (e.g. Jefferson Lab), relativistic heavy ions (RHIC), nuclear structure/nuclear astrophysics, and fundamental symmetries, respectively.

The rate of Ph.D. production has held relatively steady since 2004. It is clear that any significant cuts to the research budgets at universities will decrease the size of the future workforce, flying in the face of recommendations to increase Ph.D. production by 20%. Employment information about these graduates has been collected in various studies. In a recent study, Michael Thoennessen (private communication) found an approximate breakdown of employment as follows:

- 40% at colleges or universities
- 10% by government or national security organizations
- 10% in the nuclear weapons complex (LANL/LLNL)
- 17% at other national laboratories
- 6% in industry
- 7% in medical applications
- 10% in other areas

Large experimental facilities produce broad scientific opportunities for both experimental and theoretical studies. The organizations mount robust outreach programs, which draw young people into science. The discoveries made convey the excitement of working in STEM fields, and the myriad research opportunities attract not only universities and four-year colleges, but also high school teachers and students. Expenditures on facility operations produce jobs and economic output which is magnified beyond the immediate payroll of the facility. The resulting employment spins off into other scientific, technical, construction, and support fields. Thus closure of a major facility or failure to pursue construction of the next major facility will severely impact the ability of the Nuclear Science research enterprise to provide the needed nuclear workforce for the nation.

VI. Budget Options and the Future Program

Introduction

For over three decades, the U.S. nuclear science program has been guided by a series of Long Range Plans (LRP) developed by the Nuclear Science Advisory Committee. The most recent of these plans, which was published at the end of 2007, contained four recommendations (quoted in the Introduction to this report) that provided a nuclear-science-community-driven vision for the future. Recent major investments in U.S. nuclear science at the DOE ONP have been consistent with this guidance.

The budget presented in the 2007 LRP was developed under the assumption that there would be no significant change in the size of the nuclear science workforce. Rather, following a period from 2000-2007 that focused on developing the science and applications enabled by prior investments in the 1990's, the funding increases proposed in the LRP were devoted to capital investments for new tools required to explore the next frontiers. The 2007 LRP budget, which was predicated on a doubling of the U.S. budget in the physical sciences between FY2008 and FY2018, envisioned an aggressive schedule of construction and continued operations of existing facilities. The 2007 LRP presents the nuclear-science community's view of the resources needed for a vibrant program, and is used here as reference for that purpose.

As documented in this report, significant progress has been made over the past five years toward implementing the 2007 LRP recommendations. In the past few years, the need to maintain funds for capital investments in major projects has negatively impacted research and operations budgets and has limited funds available for new initiatives. Appropriations for ONP in the FY2012 Omnibus Bill fell nearly $60 million below the President's FY2012 request. The President's request for FY2013 is about $20 million below the FY2012 appropriation. This represents a significant deviation from the LRP profile. Faced with the potential of future budgets for the ONP that continue to fall well below the LRP profile, NSAC was charged by DOE and NSF to reassess the priorities of the 2007 LRP.

The subcommittee tasked with addressing the charge has reexamined the science case put forward for each of the recommendations in the 2007 LRP. In addition, an independent, detailed review of the science was released recently by the National Research Council (NRC2012) in a report *Nuclear Physics: Exploring the Heart of Matter*, which also strongly endorses the 2007 LRP vision. The NRC2012 report accentuates the importance of each of the cornerstone areas for the future health of the field.

The subcommittee is ***unanimous*** in reaffirming the LRP vision for the field. Each of the recommendations is supported by an extremely compelling science case. If any one part is excised, it will be a significant loss to the U.S. in terms of scientific accomplishments, scientific leadership, development of important new applications, and education of a technically skilled workforce to support homeland security and economic development. Thus, budgets that do not support moving forward with this vision require very careful analysis and difficult decisions.

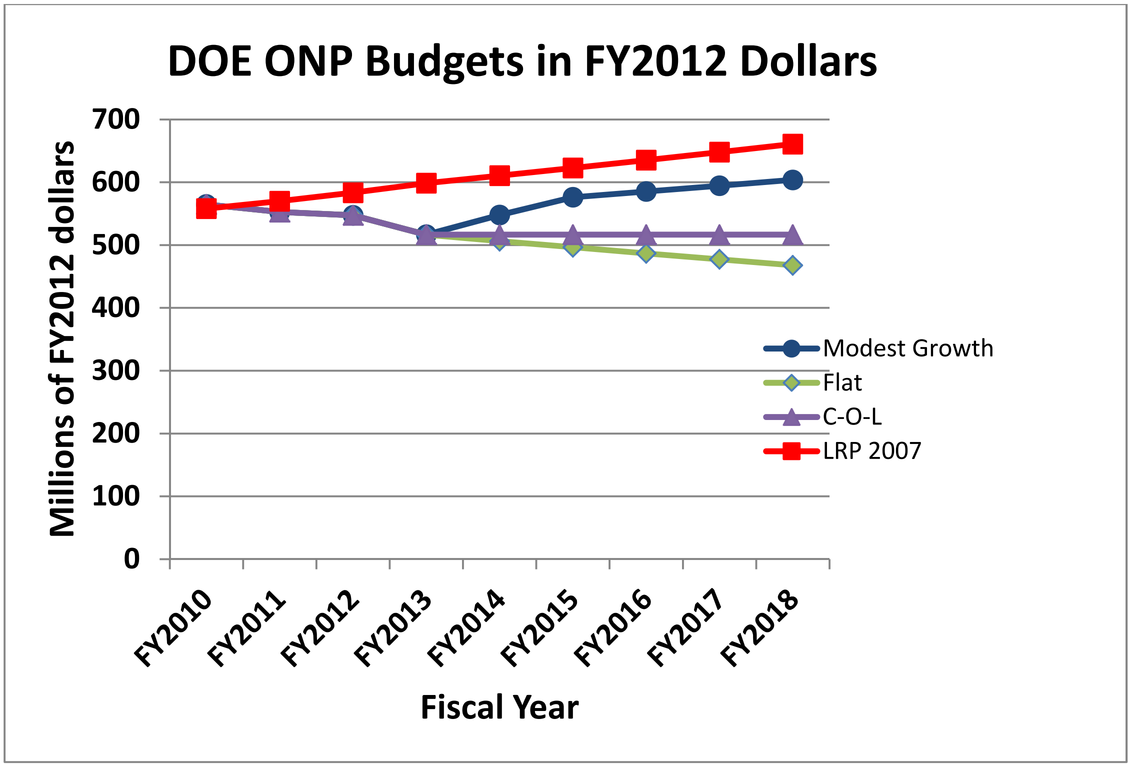
Budget Scenarios

In considering budget options, it is important to understand the present distribution of funds in the programs at the DOE ONP and the NSF. For the most recently enacted budget, FY2012, the breakdown of the ONP appropriation of $547.4 M was the following. Facility operations at the two major facilities—CEBAF and RHIC—comprised about 44% of the FY2012 budget. Including operations at other smaller facilities, the total was about 49% of the budget. The remaining FY2012 budget was split between experimental research (20%), facility construction and major equipment initiatives (16%), theoretical research (6%), applications that include the isotope and nuclear data programs (5%), and other activities (4%). The ONP research funds that support the Ph.D. level workforce for experimental programs were divided among the four cornerstone areas with 24% for relativistic heavy ion physics, 26% for hadronic physics, 17% for nuclear structure and nuclear astrophysics, and 12% for fundamental symmetries and neutrinos. Theoretical nuclear physics, which links and encompasses all four cornerstone areas, was 21% of the research budget. The NSF funding for nuclear science in FY2012 was $48.3 M. Approximately 44% of this support was for operations and research at the NSCL. In addition, NSF supported research grants in hadronic physics, nuclear structure and nuclear astrophysics, relativistic heavy ions, and fundamental symmetries and neutrinos. It also supported the Joint Institute for Nuclear Astrophysics, which is a Physics Frontier Center, and two university laboratories for nuclear structure and astrophysics.

As was noted, the FY2012 appropriation was significantly below the President's 2012 request. This resulted in closure of HRIBF that substantially reduced capabilities and beam time for experiments in nuclear structure and astrophysics, less support than was planned for continued construction of the 12 GeV CEBAF Upgrade, less operations support and thus fewer days of operation at RHIC and ATLAS, and a reduction in research funding. With the fiscal problems facing the U.S., it is unlikely that the LRP profile can be achieved in the next few years. As alternatives, three budget scenarios were considered by the subcommittee. These different scenarios—flat-flat funding and cost-of-living budgets based on the FY2013 President's request, and modest growth starting from the FY2012 appropriation projected to FY2014 and beyond—include those in the charge letter to NSAC. These budgets are shown in Fig. VI-1 in FY2012 dollars and in as spent dollars. Inflation was assumed to be 2% per year in deriving the budget numbers for the out years.

The President's ONP request for FY2013 is down over $20 million in actual dollars from the enacted FY2012 budget. The subcommittee endorsed the ONP's response to this budget, which was to spread the funding shortfall throughout the program if the yet-to-be-passed FY2013 appropriation is near this level, as the appropriate response in the short term. The major problems that this produces include further delays in the 12 GeV CEBAF Upgrade construction project, a severely curtailed experimental run at RHIC for 2013, an across the board reduction in research support, and a drop in the planned support for the pre-construction funding for the FRIB project.

The ONP budgets are driven by the large facilities. Consequently, major cuts in those budgets over several years cannot be absorbed by spreading the impact throughout the program; the cuts would be large enough to depress several programs below scientifically sustainable levels. Instead, strategic realignment is needed to close one of the two existing large facilities or not con-



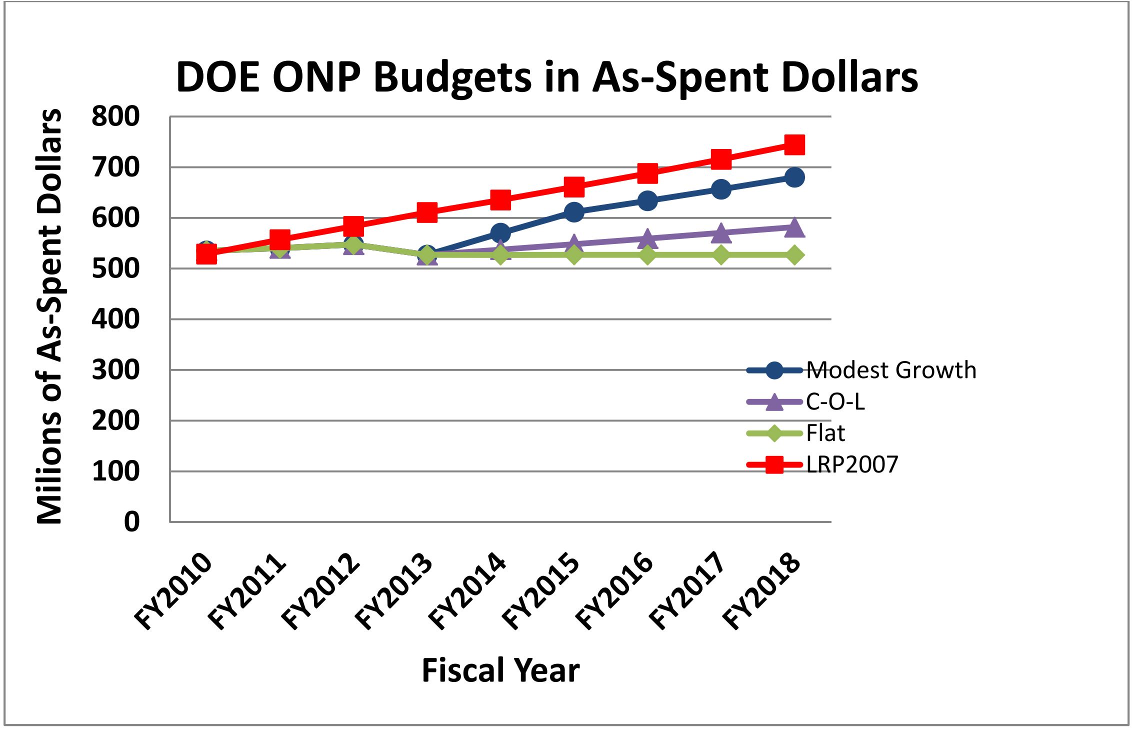


Figure VI-1: Budget scenarios considered by the subcommittee. The top panel gives the numbers in FY2012 dollars for modest growth, flat funding, and cost of living. For comparison, the 2007 LRP line is shown corrected for inflation and the isotopes program. The bottom panel shows them in as spent dollars with an inflation rate of 2% for FY2014-FY2018. The modest growth budget corresponds in FY2014 to a return to the cost-of-living-adjusted (COLA) FY2012 budget, with an additional increase in FY2015 to the level corresponding to steady growth at 1.6% per year since FY2012. Subsequent years then grow annually at 1.6% above COLA.

struct FRIB. Any of these options will result in a much smaller research effort in the future and a significant loss of science and potential applications. The future science programs associated with the upgraded CEBAF, RHIC, and FRIB have been discussed in section II of this report. The associated science will be lost if one of the facilities is closed or FRIB construction is terminated. Additional losses for the U.S. program beyond the science are associated with each option. In an attempt to summarize this, concise statements of the science that would be lost and the other associated losses are enumerated later in this section for each of the three options.

Budget Choices

The budget labeled 'Modest Growth' in Fig. VI-1 tracks well below the 2007 LRP profile. The modest-growth budget scenario can support operations at CEBAF and RHIC, FRIB construction, and a targeted program in fundamental symmetries and neutrino physics. Compared to the FY2011 appropriation, it requires significant cuts in operational time at the facilities and it returns research funding to the already strained FY2012 level. It will provide minimal funds for the start of new major equipment initiative projects. It is a budget that can sustain the momentum in the U.S. nuclear science program and not lose a major part of the science discussed in the report. It will provide the impetus needed to promote future faculty positions at research universities and will continue to attract students to the field. However, Ph.D. production will decline due to reduced research budgets, and progress on the science will be slowed. Some very important projects will have to be delayed or abandoned due to lack of funding for the equipment needed to carry them out. Following this budget scenario will slow the progress in the field but it will not have the devastating consequences of the no growth budget scenarios.

Budgets through FY2018 that provide no growth from the FY2013 President's request would require a major change in the ONP program. The flat-flat budget scenario shown in Fig. VI-1 would yield a declining program through FY2018. It would not support a program that constructs FRIB and continues operations at CEBAF and RHIC. A budget based on cost-of-living increases starting with the FY2013 President's request would not provide enough additional support to construct FRIB and continue operations at CEBAF and RHIC.

Subcommittee Deliberations

In order to answer the charge before NSAC, the subcommittee looked in detail at the past science accomplishments and the prospects for the future. Input to the subcommittee from the community was provided through White Papers, written comments, and presentations at a meeting in September, 2012, whose agenda is attached as Appendix D. Guidance in the assessment also was obtained from the NRC2012 report, which chronicles the many scientific discoveries that have come from U.S. nuclear science research over the past decade. With that important document now generally available, the subcommittee chose to stress the potential of the on-going and future science programs in this report.

The future science potential was a major ingredient in the subcommittee's assessment of how the budget scenarios discussed above would impact the field. Of the options considered, **the subcommittee was unanimous in endorsing the modest growth budget scenario as the minimum level of support that is needed to maintain a viable long-term U.S. nuclear science**

program that encompasses the vision of the LRP. This endorsement, which was made fully recognizing the sacrifices that it would entail, preserves the tools needed for both the present and future program. It preserves a path to realize the long-term vision outlined in the 2007 Long Range Plan, in which there are two large nuclear science facilities in the U.S.: FRIB, devoted to the study of complex nuclei and their applications, and an Electron-Ion Collider (EIC) focused on questions at the frontier of QCD and the nature of the interactions of quarks and gluons.

The subcommittee carefully looked at the implications for the field today and into the future of potential cuts that would have to be made in order to accommodate no-growth budgets and determined that there was no reasonable choice open to the community. If CEBAF or RHIC were closed, or if construction on FRIB were terminated, more than 25% of the scientific workforce in the field would be negatively impacted in each case. With a premature closure of either CEBAF or RHIC, the impact would be rapid and abrupt. With the termination of FRIB construction, the impact would be less abrupt but the end result would be the same. Within a few years, the scientific leadership for a cornerstone area of nuclear science would be ceded to other countries. The size of the field would be substantially reduced, with corresponding loss of opportunity for the development of new applications, for the education of a workforce skilled in nationally important areas, and for the U.S. to retain a position of shared leadership in worldwide nuclear science. In addition to the loss of science and the loss of U.S. leadership that would result from any of these actions, the nuclear science community would lose significant contributions to the program from non-federal sources, some of which have been made and others that are about to be made. Below, we summarize these losses.

A CEBAF Closure

When the 12 GeV CEBAF Upgrade is completed, it will open up a new frontier in nuclear science. Its unique capabilities will enable nuclear scientists to study excitations of the gluon field and to produce tomographic images of the interior of the proton, revealing new aspects of the underlying dynamics and interactions between its quark and gluon constituents. It represents a major step toward our goal of understanding the complex structure and properties of atomic nuclei directly from QCD. It will also enable sensitive new searches for forces and particles beyond the Standard Model that cannot be carried out anywhere else. The 12-GeV CEBAF Upgrade was the first recommendation in the 2007 NSAC Long-range Plan, and advances, discoveries, and opportunities that have emerged since then make its scientific case even more compelling. This has recently been endorsed in the NRC2012 report: "By capitalizing on … the ongoing upgrade of the continuous electron beam accelerator facility (CEBAF) at the Thomas Jefferson Accelerator...nuclear physicists will confront new opportunities to make fundamental discoveries and lay the groundwork for new applications."

Planning and investment in the 12 GeV CEBAF Upgrade since 2007 have put nuclear scientists at the doorway to this new science. The $310 million construction project is approximately 70% complete, and the 12-GeV scientific program will begin within two years. Closing CEBAF now, following very considerable U.S. investment in the facility and at a time when the 12-GeV scientific program is poised to begin, would discard the enormous benefits of this investment and abdicate U.S. leadership in hadronic physics. A unique opportunity to create and study the excited gluonic field would be gone. The program to build on the advances of the quark-gluon structure and dynamics to perform three-dimensional tomography of the proton would not be carried out. The opportunity to understand the orbital motion of the valence quarks and their contribution to the spin of the proton, a fundamental question in QCD, would be lost. A program of correlation measurements to probe the short-range nuclear force would not be carried out. A unique experimental technique measuring neutron distributions in heavy nuclei that impacts our understanding of neutron stars would go unexplored. Unique experiments to probe beyond the Standard Model of fundamental interactions, using high precision techniques and measurements to search for particles associated with dark matter, would not be performed. Closing CEBAF, with its unique world-class facility and compelling science program made possible by recent large investments in its upgrade, would end U.S. leadership in a field that it has led for decades.

With a CEBAF closure, it is likely that Jefferson Lab would be closed. As a direct consequence, the U.S. would also lose a world-leading effort in cutting-edge accelerator technology. A world-class theory effort, which not only drives the 12-GeV program, but also has broad impacts on nuclear physics in general, would be dismantled. And the infrastructure support for the free-electron laser that was developed for the Office of Naval Research would be lost.

A RHIC Closure

As stated in the NRC2012 report, "by capitalizing on strategic investments, including . . . the recently completed upgrade of RHIC . . . nuclear physicists will confront new opportunities to make fundamental discoveries." Closing RHIC at this time would leave unexploited a major fraction of the investments, both intellectual and financial, made by the United States in the science of quark-gluon plasma over the past decade. Without the unique flexibility and capability of the newly upgraded RHIC, critical regions of the phase diagram of quark-gluon plasma would remain unexplored for our lifetimes. There would be no way to use the different and unique capabilities of RHIC and the LHC to reach a comprehensive understanding of the most perfect liquid in nature – how it moves and how it is assembled from its quark and gluon constituents. Some crucial measurements can only be made at RHIC, others only at the LHC, and in many cases the payoff comes only from combining measurements at both. RHIC also collides protons, and it is the only accelerator in the world that does so with control over their spins. Ceasing RHIC operations now would terminate an international program that is elucidating the origins of the spin of the proton just as it is providing significant new insights through unique measurements of the contributions to the proton spin made by the spins of gluons and antiquarks. Closing RHIC at this time would be akin to abandoning superconductivity research just before the key experimental discovery of Josephson tunneling, which demonstrated how a superconductor works, or abandoning the Hubble telescope just after seeing its first high quality images.

Understanding how quark-gluon plasma emerges from the fundamental microscopic laws of nature requires probing this new state of matter discovered at RHIC with precision, at varying resolutions and varying temperatures, which can only be accomplished using RHIC and the LHC together. Discoveries from RHIC have motivated new measurements in LHC heavy ion collisions, and we are now seeing those measurements posing questions that only RHIC can answer. The RHIC program for the coming decade builds on significant recent investments, including the intensity upgrade (completed in 2012, three years early and at about a tenth of the originally estimated $100M cost), the new EBIS source (a joint project of NASA and the DOE) that provides tailored collision geometries, and new state-of-the-art detectors. These investments by the United States and its international partners, including a key part of the overall $130 M contribution from Japan, have transformed RHIC into a machine with new and unique capabilities that is just now taking its first steps. For example, the crucial, high precision measurements of heavy quark "tracers" require several years of running of the new high-intensity RHIC. During this period, the new intensity together with the new capabilities of EBIS would enable experiments at RHIC to quantify the fluidity of quark-gluon plasma as well as its quantum fluctuations and to probe dynamical processes in quark-gluon plasma analogous to those thought to be responsible for the excess of matter over antimatter in the universe. The discovery of the critical point in the phase diagram requires several years of running, following the ten-fold increase in intensity of lower energy beams at RHIC expected in 2017. The advanced detectors for high-rate "jet" physics, a new microscope focused on resolving the constituents of quark-gluon plasma, would come online on the same timescale. The coming decade at RHIC promises to be an era of discovery, precision, and precision-enabled discovery.

If the newly upgraded RHIC were closed now, the United States would risk losing a world-class accelerator division, a group whose technological breakthroughs enabled the RHIC intensity increase to be so much less expensive than initially projected, and whose expertise in collider operations represents key future discovery potential at many current and future frontiers of science. It would immediately jeopardize the ability of the DOE to produce the required quantities of important medical isotopes in clinical use that are made using the Brookhaven Linac Isotope Producer, which uses RHIC components and operations staff. It would also jeopardize the viability of the NASA space radiation program that is dependent on the operations of the RHIC complex. It would adversely impact many other activities of one of the major multi-purpose national laboratories in the U.S. It would terminate a vital partnership with Japan, whose investments have substantially enhanced U.S. nuclear physics. And, it would decimate quark-gluon plasma science while simultaneously ceding leadership in a new field that the U.S. has led for its first decade and is poised to lead in the decade to come.

Terminating FRIB Construction

If the Facility for Rare Isotope Beams (FRIB) were not built, the U.S. would cede leadership in the core areas of nuclear structure and nuclear astrophysics. It would lose critical capabilities for understanding the generation of nuclei in the cosmos, and for exploring the fundamental processes underlying the stellar explosions and x-ray bursts measured by current and future Earth and space-based observatories. FRIB would have unique capabilities to study very neutron-rich matter; without it the limits of nuclear stability would not be determined. The capabilities to elucidate the basic processes of nuclear fission and fusion would be lost in the U.S. Key isotopes with characteristics important to medical applications and research and key experimental clues to the development of a comprehensive theory of all nuclei would remain out of reach. Important applications to nuclear medicine, environmental protection, reactor design, nuclear waste destruction, stockpile stewardship, and nuclear forensics would be lost.

Today, the NSCL primarily provides the essential rare isotope tools for the U.S. community, but these capabilities will be surpassed by next-generation rare isotope facilities in Europe and Asia. The recent NRC2012 report listed FRIB as a key recommendation and urged that "The Department of Energy's Office of Science, in conjunction with the State of Michigan and Michigan State University, should work toward the timely completion of the Facility for Rare Isotope Beams and the initiation of its physics program." With its unique suite of high-intensity rare isotope beams FRIB would be a leader of the field. If FRIB is not built, leadership in this critical area of science will pass to other countries.

About one-third of the nuclear scientists in the U.S. are actively designing experiments and developing theory for research with FRIB. The new facility would provide training for the next generation of nuclear scientists and it would attract top talent into fields with critical applications, one being nuclear chemistry where a 2012 National Research Council report has documented a critical need. FRIB is a unique partnership between the federal government and Michigan that will deliver this major facility in a cost effective way, with Michigan providing $94.5 million in cost share funds that go toward construction and currently over $300M of planned or established additional contributions. A project team is in place and the DOE Office of Project Assessment has stated that FRIB is ready to begin construction. If the U.S. were to abandon FRIB, it would likely lead to the closure of NSCL.

As stated in the 2007 National Research Council report on Scientific Opportunities with a Rare-Isotope Facility in the United States, and reaffirmed in the NRC2012 report, "nuclear structure and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the United States. Moreover, nuclear structure-related research provides the scientific basis for important advances in medical research, national security, energy production, and industrial processing. Historically, scientific and technological developments in nuclear science have had extremely broad impact… Failure to pursue a U.S.-FRIB would likely lead to a forfeiture of U.S. leadership in nuclear-structure-related physics and would curtail the training of future U.S. nuclear scientists."

No Growth Budgets

In light of the substantial commitment that has been made to upgrade CEBAF, under all budget scenarios the subcommittee recommends completing the upgrade and capitalizing on the science that it enables.

If a decision were made to force the U.S. nuclear science community to downsize through budgets that provide no growth over the next four years, a choice would have to be made that would fundamentally change the direction of what remained of the field.

Because of the superb science lost in either shutting down RHIC or terminating construction on FRIB, the committee was not able to make a choice based on scientific merit alone. Based on additional considerations of timing of the budget crisis relative to the status of the ongoing construction initiative, the subcommittee vote, while closely split, resulted in a slight preference for the choice that proceeds with FRIB. This choice secures the significant non-ONP contributions that are critical to the cost-effective construction of FRIB, ensures a leading position for the U.S. in the central area of nuclear structure and nuclear astrophysics based on FRIB's unprecedented science capabilities.

This slight preference arises in the context of facility timelines and the approximate profile for FRIB construction, presented to the subcommittee as a snapshot of the field. If this budget exercise had occurred in a near future year, this snapshot would have changed, and the choice might well have been different.

Conclusions

In developing this report, the subcommittee has considered the impact on the U.S. nuclear science program under three different budget scenarios. Two of them provide no growth. The third would provide modest growth. The recommendations that were made for these different scenarios must be viewed as a snapshot in time that reflects the state of the field today. This view led the subcommittee to conclude that under all scenarios we must capitalize on the investment that has been made to upgrade CEBAF.

With no growth in the budget in the next four years, nuclear science must relinquish a major part of its program. If we close RHIC now, we cede *all* collider leadership, not just the high-energy frontier, to CERN and we lose the scientific discoveries that are enabled by the recent intensity and detector upgrades at RHIC. If we terminate FRIB construction, future leadership in the cornerstone area of nuclear structure and nuclear astrophysics will be ceded to Europe and Asia. In addition a window of opportunity to construct FRIB with significant non-federal resources pledged to the project will close and is not likely to reopen. In all such scenarios, very significant opportunities are lost in terms of applications of nuclear science, and for education of a workforce that is highly skilled in nationally important areas.

There are alternate paths to the two no-growth scenarios. The budget profile laid out in the 2007 Long Range Plan defines what is needed for a vibrant U.S. program in nuclear science. This report presents a modest growth budget option for the near term that falls well short of the LRP profile and requires significant sacrifices be made relative to the LRP vision. But the modest growth budget will allow the U.S. to preserve the tools that enable our science, and to preserve a path to the long-term vision outlined in the LRP in which there are two large U.S. facilities, one devoted to the study of complex nuclei and the other to questions at the frontiers of QCD. The subcommittee is convinced that it represents the minimal budget for a viable U.S. program that maintains leadership in the core areas of nuclear science.

APPENDICES

Appendix A

Subcommittee Membership

NSAC Subcommittee on the Implementation of the Long Range Plan

Subcommittee Members

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Appendix B

Charge Letter to NSAC

U.S. Department of Energy
and the
National Science Foundation

April 5, 2012

Dr. Donald Geesaman
Chair
DOE/NSF Nuclear Science Advisory Committee
Argonne National Laboratory
9800 South Cass Avenue,
Argonne, Illinois 60439

Dear Dr. Geesaman:

In 2007 the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) completed work on a Long Range Plan for nuclear science for the decade. This plan provided a roadmap for the development of new and existing facilities to maintain U.S. leadership in nuclear science, including completion of the 12 GeV CEBAF Upgrade at Jefferson Lab, and construction of the Facility for Rare Isotope Beams (FRIB). The plan also recommended a targeted program of experiments on fundamental symmetries and a luminosity upgrade to determine the properties of a new state of matter discovered at the Relativistic Heavy Ion Collider. The NSAC identified the need to maintain funding above the FY 2007 constant-effort level to effectively utilize the nuclear science program's facilities, mount strong university and theory programs, and develop new research capabilities.

DOE and NSF are making significant progress toward achieving the vision of the 2007 Long Range Plan for Nuclear Science. However, DOE and NSF now seek your advice to continue the vision in the Plan so that the recommendations can move forward in light of projected constrained budgets.

We seek advice from NSAC on implementing the priorities and recommendations of the 2007 Long Range Plan in light of projected budgetary constraints and for guidance on developing a plan to implement the highest priority science in the context of likely available funding and world-wide capabilities. We request that NSAC examine the existing research capabilities and scientific efforts, assess their role and potential for scientific advancements, and advise the two agencies regarding the time and resources needed to achieve the planned programs. Your report should describe how to optimize the overall nuclear science program over the next five years (FY 2014-2018), under at least the following funding scenarios for the nuclear science budgets at the two agencies: (1) flat funding at the FY 2013 request level, and (2) modest increases over the next five years.

Based on the priorities and opportunities identified and recommended in the 2007 Long Range Plan, the report should discuss what scientific opportunities will be addressed, and what existing and future facilities and instrumentation capabilities would be needed by the Federal nuclear science program to mount a productive, forefront program for each of the funding scenarios.

NSAC should submit the report by January 2013. We are aware that this is a difficult task. However, the involvement and input of the research community is essential to inform the Department's decisions regarding the strategy for implementing a world-leading U.S. Nuclear Physics program in times of fiscal constraint.

Sincerely,

W. F. Brinkman
Director
Office of Science

Edward Seidel
Assistant Director
Directorate for Mathematical
and Physical Sciences

Appendix C

Charge Letter to Subcommittee

Donald F. Geesaman
Distinguished Argonne Fellow

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Argonne
NATIONAL LABORATORY

May 1, 2012

Prof. Robert Tribble
Cyclotron Institute
Department of Physics and Astronomy
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Dear Bob,

As you know William Brinkman, Director of the Office of Science at DOE, and Edward Seidel, Associate Director for the Directorate of Mathematical and Physical Sciences at the NSF, have charged NSAC to provide advice on implementing the priorities and recommendations of the 2007 NSAC Long Range Plan in light of projected budgetary constraints and for guidance on developing a plan to implement the highest priority science in the context of likely available funding and world-wide capabilities.

The charge, of which you have a copy, asks that the report should describe how to optimize the overall nuclear science program over the next five years (FY2014-2018) under at least two budget scenarios: (1) flat funding at the FY2013 request level and (2) modest increases over the next five years.

I am writing to formally ask you to serve as the Chair of an NSAC subcommittee to consider this charge and report back to NSAC. The work of this subcommittee is of utmost importance for the future of nuclear science, both for the U.S. and the international science community. Based on the priorities and opportunities identified and recommended in the 2007 Long Range Plan, the report should discuss what scientific opportunities will be addressed and what existing and future facilities and instrumentation capabilities would be needed to mount a productive forefront program for each of the funding scenarios. It should also present what opportunities would be lost in each scenario. These opportunities should include the impact on education and training of the workforce in nuclear science.

The time scale of the charge requires NSAC to submit its report by January 2013. Therefore I must ask your subcommittee to submit its report to NSAC by 7 January 2013. I realize this is a heavy responsibility. I and our whole community will, once more, owe you an enormous debt of gratitude.

Sincerely yours,

Donald F. Geesaman

Appendix D

Schedule for Meeting on September 7-9, 2012

NSAC Subcommittee Meeting Agenda
Hilton Hotel & Executive Meeting Center
1750 Rockville Pike
Rockville Maryland 20852

Thursday, September 6
19:30 – 21:30 – Closed Executive Session

Friday, September 7

RHI

08:00 – 08:45 – W. Zajc, RHI Overview

08:45 – 09:00 – S. Aronson, BNL Strategy

09:00 – 09:45 – S. Vigdor, RHIC Plans

09:45 – 10:15 – P. Sorenson, Soft Probes

10:15 – 10:30 – Coffee Break

10:30 – 11:00 – Y. Akiba, Hard Probes

11:00 – 11:30 – U. Wiedemann, Theoretical Issues and LHC Perspective

11:30 – 11:45 – S. Vigdor, Wrap Up

11:45 – 12:30 – Executive Session with RHIC management

12:30 – 13:30 – Closed Executive Session and lunch

Fundamental Symmetries and Neutrinos

13:30 – 14:15 – Fundamental Symmetries overview – M. Ramsey-Musolf

14:15 – 15:00 – Neutrinos overview – H. Robertson

15:00 – 15:20 – JLab Parity experiments – K. Paschke

15:20 – 15:40 – EDM overview – B. Filippone

15:40 – 16:10 – Other FS experiments – D. Hertzog

16:10 – 16:40 – ββ-decay overview – S. Freedman

16:40 – 17:15 – Neutrino experiments – K. Heeger

17:15 – 18:00 – Executive Session with questions to focus on FS&N

18:00 – 19:30 – Dinner Break

19:30 – 21:30 – Closed Executive Session

Saturday, September 8

Medium Energy Physics

08:00 – 08:45 – R. Holt, MEP overview

08:45 – 09:05 – R. Ent, JLab Recent Accomplishments

09:05 – 09:35 – R. McKeown, JLab Future Science Program

09:35 – 09:55 – J. Dudek, Meson Spectroscopy and GlueX

09:55 – 10:15 – M. Guidal, Nucleon Imaging

10:15 – 10:30 – Coffee Break

10:30 – 10:50 – C. Rode, 12 GeV Project Status

10:50 – 11:10 – A. Hutton, Accelerator Science

11:10 – 11:30 – A. Lung, Budget Impacts

11:30 – 11:45 – H. Montgomery, Summary and Outlook

11:45 – 12:30 – Executive Session with JLab management

12:30 – 13:30 – Closed Executive Session and lunch

Low Energy – FRIB/NSCL

13:30 – 14:15 – David Dean, LE (NS&NA) overview

14:15 – 14:35 – K. Gelbke, FRIB Laboratory Overview

14:35 – 15:00 – T. Glasmacher, FRIB Project

15:00 – 15:15 – A. Gade, FRIB Science – Nuclear Structure and Reactions

15:15 – 15:30 – H. Schatz, FRIB Science – Nuclear Astrophysics

15:30 – 15:40 – Z. Lu, FRIB Science – Fundamental Symmetries

15:40 – 15:50 – G. Bollen, FRIB Science – Applications of Isotopes

15:50 – 16:05 – Discussion of FRIB Science

16:05 – 16:20 – Break

16:20 – 16:35 – B. Sherrill, Uniqueness of FRIB

16:35 – 16:50 – D. Leitner, NSCL Capabilities and Operations

16:50 – 17:15 – P. Mantica, NSCL Science Program and Results

17:15 – 18:00 – Executive Session with FRIB management

18:00 – 19:30 – Dinner Break

19:30 – 21:30 – Closed Executive Session

Sunday, September 9

Low Energy, Nuclear Astrophysics, Theory, and Computation

08:00 – 08:30 – ATLAS – G. Savard

08:30 – 09:15 – ARUNA – I. Wiedenhoever

09:15 – 10:00 – Nuclear Astrophysics (interface to NP) – A. Burrows, M. Wiescher

10:00 – 10:45 – Nuclear Theory – D. Kaplan

10:45 – 11:15 – Computational Physics – M. Savage

11:15 – 16:00 – Closed Executive Session and lunch