Report to the
Nuclear Science Advisory Committee

Guidance for Implementing the
2002 Long Range Plan

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Contents

Executive Summary

The Nuclear Science Advisory Committee (NSAC) submitted a Long-Range Plan (LRP), "Opportunities in Nuclear Science," to the Department of Energy (DOE) and the National Science Foundation (NSF) in April 2002. The LRP laid out a framework for the coordinated advancement of our field with a set of recommendations for the ongoing and future program. In the years since, our field has made groundbreaking discoveries on several of the highlighted scientific fronts— direct evidence for neutrino oscillations; observation of a new state of matter; revelations on the quark substructure of the proton; and exotic nuclei with completely unexpected properties. Furthermore, the case for the recommended new initiatives has progressed considerably, especially in the DOE report "Facilities for the Future of Science: A Twenty-Year Outlook." However, pressures on the Federal Budget are now limiting funds to implement the LRP. In a joint letter issued March 14, 2005, the Department of Energy and the National Science Foundation requested that NSAC "examine the existing research capabilities and scientific efforts [in the DOE Nuclear Physics program], assess their role and potential for scientific advancements in the context of international efforts and determine the time and resources (the facilities, researchers, R&D and capital investments) needed to achieve the planned programs. NSAC should then identify and evaluate the scientific opportunities and options that can be pursued at different funding levels for mounting a world-class, productive national nuclear science program." The enclosed report is the response to this charge.

Nuclear science is driven by fundamental investigations of the origin, evolution and structure of strongly interacting matter. Progress on our broad mission requires a balanced attack on key questions in three different, highly intertwined frontiers: (1) the strong nuclear force (quantum chromodynamics or QCD) and its implications for the origin of matter in the early universe, quark confinement, the role of gluons and the structure of the proton; (2) the study of nuclei and nuclear astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) the standard model and its possible extensions as they bear on the origin of matter and the properties of neutrinos, neutrons, and other subatomic particles.

Development of the state-of-the-art tools essential to this progress requires careful planning over decades. Our field has greatly benefited from leaders who had the foresight to recognize the need for our two flagship facilities—the Continuous Electron Beam Accelerator Facility (CEBAF) at the Jefferson Laboratory and the Relativistic Heavy-Ion Collider (RHIC) at the Brookhaven National Laboratory—which were recommended in Long-Range Plans over two decades ago. CEBAF and RHIC are innovative instruments for investigations of QCD in nuclear matter, and they have no peers in the world. CEBAF has been in full operation for less than a decade; RHIC came on-line at the start of the new millennium. Return on investment for both has been swift with major new discoveries and results that will rewrite our textbooks. These machines are complementary, probing very different yet related aspects of the underlying theory of the strong interaction.

The 2002 LRP also identified a powerful new instrument for the future, the Rare Isotope Accelerator (RIA). Like CEBAF and RHIC before it, RIA would be a unique discovery tool for nuclear science. It would open vast new horizons for our field with its unprecedented capabilities to produce and study nuclei far removed from those known today.

However, in the past three years, funding for nuclear science has fallen far short of the level needed to implement the 2002 LRP. The #1 recommendation of that LRP was to *exploit the extraordinary opportunities for scientific discoveries made possible by recent investments.* Currently, our major facilities are running below full capability and the research workforce has already been reduced. The current five-year funding projections represent a serious and immediate threat to the continued operation of CEBAF and RHIC. This extremely troubling possibility triggered the charge from DOE and NSF to NSAC.

In addressing its charge, the subcommittee critically examined the priorities of the 2002 LRP. Our conclusions strongly reinforce the scientific vision of that plan. We found the discovery potential of RHIC and the science cases motivating RIA, a 12-GeV upgrade at CEBAF and new experiments in neutrino science to be even stronger today than anticipated in 2002. In the present report, we lay out the compelling science questions the field is working to answer. We consider the role of U.S. facilities and scientists, within an international context, in defining and addressing these central science issues, as well as in training a workforce to meet the Nation's growing needs for nuclear scientists. We provide specific guidance, as requested, for several budget scenarios, focusing on the scientific opportunities afforded and lost by each. All of these scenarios involve compromises from the LRP, ranging from significant to crippling.

Because accelerator facilities require sustained infrastructure and staffing for safe and reliable operation, small short-term funding cuts will result in highly magnified reductions in productivity. Long-term operation of a facility below about 50 percent of its capacity is neither cost-effective nor sustainable for an optimized program. We thus find that the two bleakest budget scenarios provided would lead to the near-term closing of RHIC or CEBAF *with no scientific justification and with far-reaching consequences for a loss of U.S. scientific pre-eminence*. These facilities are making a huge impact in nuclear science, and have large and active international user communities; both have a robust present program and a bright future. Closure of either facility now is premature—it would waste tremendous scientific opportunities, abrogate international agreements between laboratories, and severely cut the production of trained nuclear scientists. With deep misgivings, the subcommittee provides criteria in this report for choosing between these two unique facilities, if circumstances beyond our control mandate such extraordinarily severe measures.

The subcommittee found that such a serious loss of scientific potential can be avoided, albeit still with considerable disruption and delay, in a budget that builds upon the present FY05 appropriation. Very modest additional investments above that level will allow us to maintain the world's program of science carried out at RHIC and CEBAF and to preserve the unique opportunities, community, and investment made to date at these facilities. However, even such a budget scenario does not allow a timely start on construction of RIA, as would be needed to bring this facility online before 2020. The subcommittee recognizes the serious long-term implications for the field if major investments in future facilities are delayed too long, but at this point supports the LRP priority given to exploiting near-term discovery potential at existing facilities. This priority will have to be revisited within the next few years if new funds for RIA construction are not found.

We conclude by reiterating that major investments in its scientific infrastructure over the past two decades have made nuclear science in the United States the best in the world. As our report describes, extraordinary opportunities for research at these superb facilities during the coming decade have been identified. Relatively modest incremental investments, especially the upgrade of CEBAF to 12 GeV beam energy and improvements to the RHIC detectors, will allow the realization of these opportunities. The construction of new facilities described in the Office of Science document "Facilities for the Future of Science: A Twenty Year Outlook" and elsewhere—foremost among them the Rare Isotope Accelerator and a multipurpose deep underground science laboratory—will allow U.S. nuclear science to retain its world leading position in the longer term. In contrast, a substantial reduction of annual budgets below the FY05 level will force us to give up a large part of our current strategic advantage without scientific justification. Such a development would constitute a major blow to the scientific competitiveness of our nation. We are hopeful that it can be avoided.

I. Introduction

The Department of Energy (DOE) and the National Science Foundation (NSF) support a broad portfolio of nuclear science research that seeks answers to key questions about the composition and evolution of the universe. With investments made in new and upgraded facilities over the past two decades, the U.S. continues to lead the world in this strategic field of science. Indeed nuclear scientists from many countries have made large investments in manpower and equipment at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory (JLab), the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University in order to carry out forefront research at these unique facilities. Considering all facilities around the world, many of the most significant, exciting nuclear science discoveries have come from these U.S. labs.

The DOE and NSF have relied heavily on advice from the Nuclear Science Advisory Committee (NSAC) to guide the critical prior national investments in nuclear science. This arrangement, established nearly 30 years ago, has worked remarkably well. For nearly three decades, the nuclear science community has maximized the nation's research investment by developing, through NSAC, a series of long range plans (LRPs) to guide federal funding in the field. These plans often have required difficult decisions to strike the proper balance between investing for the future with maximizing research productivity today. But they have yielded a world-class program in nuclear science. We are now poised to address the primary mission of nuclear science in the coming decade: ***explaining, at the most fundamental level, the origin, evolution and structure of the baryonic matter of the universe—the matter of stars, planets, and life itself***.

Nuclear scientists today attack this overarching problem through three broad but highly related research frontiers: (1) the strong nuclear force (quantum chromodynamics or QCD) and its implications and predictions for the origin of matter in the early universe, quark confinement, the role of gluons and the structure of the proton; (2) the study of nuclei and nuclear astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) the standard model and its possible extensions as they bear on the origin of matter and the properties of neutrinos, neutrons, and other subatomic particles In this report, we have identified questions that typify some of today's nuclear science issues. The list is surely not all-inclusive, but rather indicative of the subcommittee's view of the current programs and priorities in nuclear science research.

Quantum Chromodynamics:

- *What is the nature of the quark-gluon matter of the early universe and what transitions led to our present world of protons and neutrons?*
- *Where is the glue that binds quarks into strongly interacting particles, and what are its properties?*
- *What is the internal landscape of the proton?*
- *What does QCD predict for the properties of nuclear matter?*

Nuclei and Nuclear Astrophysics:

- *What binds protons and neutrons into stable nuclei and rare isotopes?*
- *What is the origin of simple patterns in complex nuclei?*
- *When and how did the elements from iron to uranium originate?*
- *What causes stars to explode?*

Standard Model:

- *What are the masses of neutrinos and how have they shaped the evolution of the universe?*
- *Why is more matter than antimatter seen in the present universe?*
- *What are the unseen forces that disappeared from view as the universe cooled?*

Finding answers to these fundamental questions poses a significant challenge for our field. Fortunately, with prior wise investments and careful stewardship, we have some of the necessary tools in hand for this task. But our community now finds itself at a crossroads. The *2002 LRP for Nuclear Science*, the most recent in the series of LRPs, laid out a comprehensive strategy for maintaining world leadership—framing, communicating, and executing a strategic vision—in key segments of the field. The foundations of this strategy were captured in the following four recommendations.

1. *Recent investments by the United States in new and upgraded facilities have positioned the nation to continue its world leadership role in nuclear science. The highest priority of the nuclear science community is to exploit the extraordinary opportunities for scientific discoveries made possible by these investments. Increased funding for research and facility operations is essential to realize these opportunities.*

Specifically, it is imperative to

- Increase support for facility operations—especially our unique facilities, RHIC, CEBAF and NSCL—which will greatly enhance the impact of the nation's national nuclear science program.
- Increase investment in university research and infrastructure, which will both enhance scientific output and educate additional young scientists vital to meeting national needs.
- Significantly increase funding for nuclear theory, which is essential for developing the full potential of the scientific program.

2. *The Rare Isotope Accelerator (RIA) is our highest priority for major new construction. RIA will be the world-leading facility for research in nuclear structure and nuclear astrophysics.*

The exciting new scientific opportunities offered by research with rare isotopes are compelling. Building RIA is essential to exploit these opportunities and to ensure world leadership in these areas of nuclear science. RIA will require significant funding above the nuclear physics base. This is essential so that our international leadership positions at CEBAF and at RHIC be maintained.

3. *We strongly recommend immediate construction of the world's deepest underground science laboratory. This laboratory will provide a compelling opportunity for nuclear scientists to explore fundamental questions in neutrino physics and astrophysics.*

Recent evidence for neutrino mass has led to new insights into the fundamental nature of matter and energy. Future discoveries about the properties of neutrinos will have significant implications for our understanding of the structure of the universe. An outstanding new opportunity to create the world's deepest underground laboratory has emerged. This facility would position the U.S. nuclear science community to lead the next generation of solar-neutrino and double-beta-decay experiments.

4. *We strongly recommend the upgrade of CEBAF at Jefferson Laboratory to 12 GeV as soon as possible.*

The 12-GeV Upgrade to the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. The energies achievable by the upgrade will enable experiments that will provide new insights into the structure of the nucleon, the transitions between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

In the past three years, funds for nuclear science have fallen short of those needed to implement even the first recommendation of the 2002 LRP. With the FY05 appropriation, operations support at existing facilities has grown by about 10 percent (in FY02 dollars) which has helped to improve the beam availability at our major facilities. During this same period, the research budget has been held at a constant level of effort. Indeed operations support now represents nearly 60 percent of the DOE Nuclear Science budget, with 86 percent of these funds targeted to support our two major facilities, CEBAF and RHIC. During this same time, two small initiatives identified as new opportunities in the LRP—the Fundamental Neutron Physics Beam Line and GRETINA—have been started by DOE.

The last LRP was initiated in July 2000, when federal budget deficits had all but disappeared and budget projections painted a very positive picture for the start of the new millennium. But part of the charge to the authors of the LRP was to discuss the program that could be carried out with a constant level-of-effort budget in the period from FY02 to FY12. The following excerpt gives the advice of the 2002 LRP under that funding restriction.

> "In such a scenario, the current breadth of the program could not be sustained. To maintain world leadership in a few core areas of the field, difficult choices would have to be made. RHIC and CEBAF would continue to operate as world-leading facilities, but their upgrades would be delayed. We would have no opportunity to build RIA or NUSL, and a number of smaller facilities might have to be closed. A significant retrenchment in the research portfolio of the field would be required, a move that would be inconsistent with the thrust of this and previous long-range plans."

Already the effects of a budget at near constant-level-of-effort are being felt. Three facilities—the Bates accelerator at MIT, the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory, and the 88-in. cyclotron at the Lawrence Berkeley National Laboratory—have been closed as user facilities. A CD-0 has been signed for the 12-GeV Upgrade at CEBAF, but funding has not been identified to carry it out. A CD-0 has been issued for RIA, and modest funding for R&D has kept the option open for its construction, but new funding for it has yet to be allocated.

Continued funding at a constant FY05 level of effort would allow our two flagship facilities, RHIC and CEBAF to operate into the foreseeable future. But this level of funding would provide neither the flexibility to exploit major new discoveries in a timely way nor would it allow us to upgrade existing facilities without jeopardizing on-going operations. This scenario would represent a sharp departure from nearly three decades of nuclear science practice that has prudently balanced running existing programs with investing for the future. And it would not position the U.S. nuclear science community to lead the world into the second decade of the new millennium.

More stringent budgets than a constant FY05 level of effort make even the scenario above problematic. The proposed cut of 8.4 percent in the President's FY06 budget, relative to the existing FY05 appropriation, would result in an inflation-corrected *cut* of more than 5 percent from the FY02 budget level. Continued flat-flat funding for the next several years would have a devastating effect on U.S. leadership in nuclear science. Even funding at a constant level of effort with the FY06 budget as a base would not allow the U.S. nuclear science community to effectively utilize our existing facilities, much less invest in the future.

Facing potentially devastating budgets, DOE and NSF have turned to NSAC for guidance. A charge letter sent to NSAC, which is provided in Appendix A, spells out the problem:

> "Since the issuance of the Long Range Plan, the resources needed to implement the recommended program have not been identified by the agencies…. [The FY06] funding level, projected into the outyears, is not sufficient to maintain the scope of the present Nuclear Physics program and, in particular, to continue operations of the program’s two major facilities, RHIC and CEBAF, as they are presently conducted. The major initiatives recommended in the Long Range Plan, such as RIA, are not accommodated. In light of these projected budgetary stringencies and their implications for the U.S. Nuclear Physics program, the priorities and recommendations of the 2002 Long Range Plan need to be revisited. A strategic plan on how to implement the highest priority science in the context of available funding and world-wide capabilities needs to be developed."

Specifically, NSAC has been asked to "provide recommendations for an optimized DOE nuclear science program over the next five years" under three different funding scenarios:

- Flat-flat funding at $370.4 million, actual dollars
- Constant effort funding (starting with $370.4 million in FY 2006), inflated dollars
- Funding levels needed to restore research capabilities and scientific programs to mount an optimized program and to address the scientific opportunities identified in the 2002 Long Range Plan in order of their priority.

NSAC, in response to the request for guidance, created a subcommittee to focus specifically on this issue and requested that a report be sent to NSAC by mid-June 2005, as indicated in Appendix B. The subcommittee, whose membership is given in Appendix C, includes 22 members of the nuclear science community who represent the broad interests in the field. To obtain information on the present state of the nation's overall nuclear science program, the subcommittee held a meeting April 3–5, 2005, in Bethesda, Maryland. An overview of the CEBAF, RHIC, low-energy and theory programs were presented at the meeting. A copy of the agenda is included as Appendix D. Suggestions from the nuclear science community were obtained in a town meeting held at the April 2005 American Physical Society meeting in Tampa, Florida. A third meeting of the subcommittee was held in Chicago on May 4–6, 2005, to develop the findings and guidance given in this report. In addition to the three funding scenarios given in the charge to NSAC, the subcommittee considered the program that could be carried out starting at two additional FY07 base budgets and continuing them to FY11 at a constant level of effort. The subcommittee findings and the program options under different funding scenarios are described in Section V of this report.

II. Nuclear Science Today – The Subcommittee Perspective

The mission of nuclear science is to explain the origin, evolution, and structure of the baryonic matter of the universe—the matter that makes up stars, planets, and human life itself. We believe that the big bang created a hot, dense soup of equal amounts of matter and antimatter. But, as the universe expanded and cooled, a remarkable chain of events, which we are beginning to understand, led to the disappearance of antimatter, the coalescence of quarks and gluons into protons, neutrons and other strongly interacting particles, and the formation of the lightest nuclei. A hundred million years later, these light nuclei were fused together to form heavy nuclei, including the elements of life, in the cores of the first stars—a process that continues today in succeeding generations of stars. Nuclear scientists are using sophisticated measurements and theoretical analyses to piece together the various chapters in this history and to understand the properties of the matter in the current universe—the material from which we are made.

Nuclear science is an evolving discipline that builds on past discoveries to seek answers to the critical questions about the history and present character of matter. What is presented here is the NSAC subcommittee's view of our science today. In developing the report, we have identified three main frontiers that characterize our mission: (1) quantum chromodynamics (QCD) and its implications for the state of matter in the early universe, quark confinement, the role of gluons and the structure of the proton; (2) the study of nuclei and astrophysics, which addresses the origin of the elements, the structure and limits of nuclei, and the evolution of the cosmos; and (3) the standard model and its possible extensions as they bear on the properties of neutrinos, neutrons, and other subatomic particles.

The subcommittee heard presentations of ongoing and planned work at each of these frontiers. We found an enormous level of excitement and convey some of it here. But because of time constraints and the strictures of our charge—we are able to provide only a snapshot of this scientific vitality. A more comprehensive view is contained in the 2002 Long Range Plan.

To focus the science discussions and to provide signposts in our view of the field, the subcommittee developed a set of questions—grouped by scientific frontier—that are addressed in the subsequent sections of this report.

Quantum Chromodynamics

The study of quantum chromodynamics (QCD) is a major thrust in nuclear physics. By the late 1970s, it was clear that achieving a first-principles theory of the interaction between protons and neutrons—the nucleon-nucleon force—would require a better understanding of the fundamental strong interaction embodied in QCD. As theorists investigated the new theory, they realized that QCD also provides a missing link in the early evolution of the universe: in the very early epoch following the big bang, a phase transition had to occur between the primordial sea of quarks and gluons and the emergence of protons, neutrons and the eventual birth of nuclei. Nuclear physicists continue to work on critical topics in this field. Some of the questions being addressed include:

- **What is the nature of the quark-gluon matter of the early universe and what transitions led to our present world of protons and neutrons?** Quantum chromodynamics is the component of the standard model that describes the strong interaction among quarks and gluons. It predicts that soon after the birth of the universe a sea of quarks and gluons coalesced into protons and neutrons. Can we replicate that transition by temporarily freeing quarks from their normal confinement within protons and neutrons? Experiments at RHIC address these most fundamental questions by creating and studying matter with temperatures and densities found in the early universe.

- **Where is the glue that binds quarks into strongly interacting particles, and what are its properties?** Gluons and the color force they carry are the distinct features of QCD. But QCD predicts that gluons should act in ways that we have not yet observed. Unlike the photons that carry the electromagnetic force, gluons interact not only with quarks but also with each other. These self-interactions are, in fact, so strong that they confine quarks inside the proton and can contribute substantially to its mass and spin. The excitations of the confining glue may produce a whole new spectrum of "hybrid" particles that have yet to be seen. A universal ensemble of densely packed gluons may also be found in all strongly interacting particles, including nuclei.

- **What is the internal landscape of the proton?** For many years, we have known that the proton is a composite particle made up of quarks and gluons. How are the quarks distributed in the proton, and how do they move? We have partial answers to these questions from years of measurements with high-energy probes. But experiments at CEBAF following the 12-GeV Upgrade will provide an unprecedented, tomographic view of the quarks and their motion inside the proton. With these additional measurements, we will be able to map out the essential features of the quark landscape—such as the impact of quark motion on the proton's spin—and make detailed comparisons with QCD predictions.

- **What does QCD predict for the properties of nuclear matter?** QCD is a simple and elegant theory whose predictions for high-energy processes—now verified by numerous measurements—can be obtained in a straightforward way. Nevertheless, a critical step in the quest to understand strongly interacting matter is to confront the results of experiments at RHIC and CEBAF, as well as astrophysical data on the structure of neutron stars, with the quantitative implications of QCD. Doing so is exceedingly challenging, because the strong force cannot be accurately described at the relevant scales by means of analytical calculations. Future progress will require extensive numerical simulations on a scale that has never before been undertaken.

Nuclei and Nuclear Astrophysics

The study of nuclei and nuclear astrophysics is a core component of our field, connecting QCD phenomena, many-body systems, and the cosmos. Understanding the fundamental many-body problem of nuclei requires a close interplay between theory and experiment. Missing components in our current understanding must be addressed to develop a comprehensive predictive theory of nuclei that is capable, for example, of explaining the limits of nuclear existence beyond which no additional neutrons or protons can be added to nuclei. Concurrently, while great strides have been made recently to explain a variety of astrophysical phenomena, we lack the information on nuclear properties and reactions that is required to decipher satellite observations of exploding stars or the spectra of ancient stars.

Future progress in both nuclear structure and nuclear astrophysics will require new tools. The key to much of this future work is a new accelerator, the Rare Isotope Accelerator, or RIA. Some of the central questions addressed for this part of our field are:

- **What binds protons and neutrons into stable nuclei and rare isotopes?** Using our knowledge of the basic nucleon-nucleon interaction, nuclear physicists are now able to calculate the features of lighter nuclei with astonishing precision. As with other complex systems such as proteins, however, the properties of heavy nuclei cannot be easily described in terms of elementary interactions among their isolated constituents. Today, developing a comprehensive, predictive theory of these heavy, complex nuclei lies at the forefront of nuclear physics. Indeed, recent observations made possible by the emerging technology of radioactive beams demonstrate strikingly anomalous behavior in rare isotopes, indicating that our knowledge of the inner workings of the nucleus is far from complete. The study of nuclei having high neutron or proton imbalances will provide the missing links in our present understanding.

- **What is the origin of simple patterns in complex nuclei?** Complex systems often display amazing simplicities; nuclei are no exception. It is remarkable that a heavy nucleus consisting of hundreds of rapidly moving protons and neutrons can exhibit collective motion, where all particles slowly dance in unison. To fully understand this behavior, further insights gained from the study of new forms of rare nuclei are needed. Nuclear physicists expect to observe a broad range of new collective phenomena, which are predicted to emerge in neutron-rich systems. The very existence of these exotic nuclei hangs on the subtle balance between the individual motion of protons and neutrons and nuclear superconductivity.

- **Where and how did the elements from iron to uranium originate?** While we have identified the astrophysical origin of many of the elements, the production site of about half of the elements between iron and uranium remains a perplexing mystery. Current models suggest a series of rapid neutron captures on rare nuclei having excess neutrons may have occurred in a cataclysmic stellar environment, such as a supernova explosion. However, determining if the synthesis occurs in supernovae or other exotic cosmic locations will require a sophisticated interaction of theory, experiment, and observation. Progress requires significant theoretical advances as well as the production and analysis of rare isotopes well-beyond the reach of current laboratory experiments.

- **What causes stars to explode?** Thanks to the seminal work of Hans Bethe, we have known for decades that nuclear reactions fuel the evolution of stars. However, understanding how stars explode and what exotic properties their neutron star remnants retain is still a mystery. New experimental and theoretical tools and techniques are needed to determine the relevant critical nuclear reactions and structure properties.

During the past decade, we have also discovered that neutrinos play a major role in defining the fate of stars. Investigating these questions will require a new generation of experiments capable of unraveling the interactions of neutrinos with matter.

Fundamental Symmetries and Neutrinos

The forces and symmetries that were in play during cosmic evolution have shaped the landscape of nuclear matter as we know it today. Nuclear scientists have long studied the fundamental symmetries of the weak interaction responsible for the radioactive decay of matter. Indeed, the roots of the standard model lie in ground-breaking 1950s measurements of nuclear beta decay and the related discovery that the weak force does not look the same when viewed in a mirror. Recent very precise, low-energy experiments have probed the standard model to unprecedented levels. While the model has proven remarkably robust to precision tests, there are cases where small cracks are beginning to appear. If the breakdown is confirmed, we could be seeing the first signs of new physics, such as supersymmetry, which offers a candidate explanation for the dark matter of the universe.

The 1950s also marked the beginning of Ray Davis' pioneering measurements that determined the solar neutrino rate to be too low compared with theoretical expectations. The finding led to the recent discovery that neutrinos oscillate among their types; thus, more than half of the neutrinos from the sun had gone undetected in the Davis experiment, which was only sensitive to one of the three types. The neutrino "mixing" discovery also proved that neutrinos must have mass—and therefore they carry important implications to understanding the evolution of the universe. New experiments are fueling a "neutrino revolution" and their results are causing a corner of the standard model to be completely recast. Many new and important questions have been raised, which we expect to be answered in the next generation of neutrino experiments.

Today, we are continuing to push the limits of discovery and precision to find out what other forces may have shaped the history of matter. We identified three questions that summarize much of the present and near-term work in this subfield:

- **What are the masses of neutrinos and how have they shaped the evolution of the universe?** We now have clear evidence that neutrinos have mass. Neutrino oscillation experiments tell us about neutrino mass differences, but we do not know the absolute scale. To answer this question, nuclear scientists are building highly sensitive experiments on beta decay of tritium and are developing techniques to measure an extremely rare process—"neutrinoless" double beta decay. Determining the mass scale will address a number of questions in neutrino physics and will help delineate the role of neutrinos in the early evolution of the universe.

- **Why is there more matter than antimatter?** The very existence of the visible cosmos—from the galaxies to human life itself—implies that the universe contains more matter than antimatter. But the standard model does not explain how this excess matter came to be. If the cosmos had equal amounts of matter and antimatter at its birth, what caused the imbalance as it evolved and cooled? An essential ingredient is the presence of new forces that do not look the same when the direction of time—like a video—is reversed. Nuclear scientists are seeking to discover these time-asymmetric forces with new measurements of properties of neutrons, atoms, and neutrinos.

- **What are the unseen forces that disappeared from view as the universe cooled?** Most of our world is extremely well described by the standard model. But we know that this elegant model is only an incomplete version of a more comprehensive theory that describes forces of nature from the earliest moments of the universe. Both nuclear and particle physicists are searching for indications of what the more complete theory could be. The observation of neutrino oscillations has provided our first direct view of new physics. In addition to studying the properties of neutrinos, nuclear physicists are performing highly precise measurements of other particle properties to look for departures from the firm predictions of the standard model. Such departures would signal the presence of additional, undiscovered forces that played an important role when the universe was young.

In the sections below, the subcommittee has summarized the science presented to it at a meeting held in April 2005. The schedule for this meeting is given in Appendix B. The presentations were guided by a series of questions generated by the subcommittee. The science presentations focused on recent accomplishments (those not chronicled in the 2002 LRP), current work, and future plans. The presentations were organized around the three major budget categories in the DOE Nuclear Physics program: relativistic heavy ions, medium energy physics, and low-energy nuclear physics. The first two programs are completely dominated by DOE's two major facilities, RHIC and CEBAF. The third includes accelerator- and non-accelerator-based research in nuclear structure, astrophysics, fundamental symmetries, and neutrino physics. For expediency, we have preserved this organization in the science reported here.

A. The Science of RHIC

Overview

A grand intellectual challenge facing humankind is to understand the physics of the early universe. Forging connections between the physics that governs the world in which we now live and the physics of matter under extreme conditions is central to this effort. What states of matter existed at the extraordinarily high temperatures and densities inferred for the early universe? Were free quarks and gluons the dominant constituents of that matter? Why did that matter evolve into massive protons and neutrons? At the Relativistic Heavy-Ion Collider (RHIC) and its array of detectors at Brookhaven National Laboratory (BNL), scientists are poised to address these and other key intertwined questions at the frontier of quantum chromodynamics (QCD) studies.

- **How does ordinary matter get its mass?** As indicated in **Fig. II-1**, more than 98 percent of the mass of everything we see arises from the energy of the forces that confine quarks inside neutrons and protons (collectively called "nucleons"). RHIC experiments probe the nature of these confining forces and of the "sea" of gluons and quark-antiquark pairs they produce, as well as the breaking of a basic QCD symmetry associated with mass generation. Heavy-ion collisions create extraordinary conditions where QCD predicts this symmetry to be restored and quarks and gluons to be liberated from their confinement.

- **How does QCD matter behave at the extraordinary temperatures attained during the first microseconds following the big bang?** RHIC experiments have already demonstrated that these conditions are reached in the early stages of head-on collisions of gold nuclei and have revealed unprecedented and unanticipated properties of the resulting matter. For example, the matter reaches thermal equilibrium much more rapidly than predicted, and it flows as the most nearly perfect liquid ever observed. Essential follow-up measurements employing upgraded detectors and enhanced collision rates (RHIC-II) will quantify these properties vis-à-vis quantum limits and predictions for a fluid composed of liberated quarks and gluons.

- **What is the structure of the QCD vacuum, and how is it affected by high temperature and density?** In modern theories, the vacuum state is not at all "empty" but has structure allowing excitations of particle-antiparticle pairs. The QCD vacuum is particularly complex under normal conditions, but may be transformed in the extreme conditions produced in RHIC heavy-ion collisions to a simpler form, which fully reflects the symmetries of the QCD interaction corresponding to nearly massless quarks (chiral symmetry). Are these usually broken symmetries of the theory restored in this transformed vacuum state? These profound issues will be explored in high-energy heavy-ion collisions at RHIC and the planned upgraded facility, RHIC-II.

- **What are the universal properties of all strongly interacting systems in the limit of high gluon density?** A central truth of nuclear physics is that the saturation of nuclear forces causes the matter in the interior of most nuclei to be of equal density. Does a similar universal form of saturated gluonic matter (the so-called “color glass condensate”) appear in all nuclei and other strongly interacting particles when they are observed moving at very high energy? Is this gluon field saturation partly responsible for the rapid equilibration of the matter observed in RHIC heavy-ion collisions? These important questions can be addressed at RHIC, and with even greater precision using the proposed electron-ion collider facility (eRHIC).

In its first five years of operation, RHIC has developed into the world’s foremost facility for the exploration of the phases of matter governed by QCD. With the planned program of upgrades, RHIC-II (detector improvements combined with enhanced collider beam intensity) and eRHIC, (development of an electron-ion collider capability), the facility would remain at this forefront for another generation. Its unprecedented versatility and pioneering accelerator physics achievements facilitate a program combining detailed quantitative measurements of ordinary QCD matter with groundbreaking discoveries of the properties of QCD matter driven to extraordinary conditions of temperature and density. RHIC results to date have excited broad interest beyond the physics community, while also establishing unanticipated connections to the work of plasma physicists and string theorists.

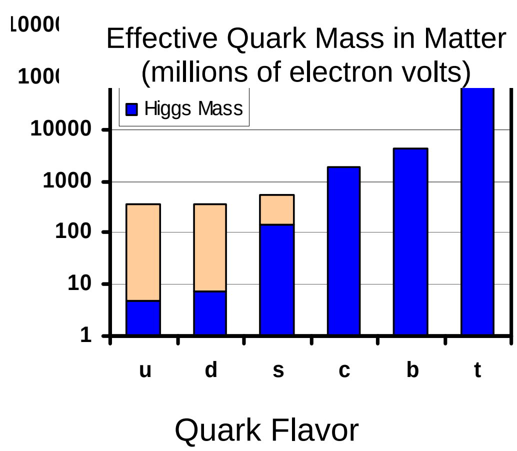

Figure II-1. Particle and nuclear physicists both seek the origins of mass. Searches for the Higgs particle at high-energy accelerators focus on the “bare” masses (blue bars in the graph), which account for the full mass of heavy quarks (c,b,t) that can be produced in high-energy collisions. But more than 98 percent of the mass of ordinary matter arises from QCD interactions (beige bars) of up (u) and down (d) quarks with other quarks, gluons and the complex QCD vacuum. Research at RHIC seeks to clarify the nature of these interactions and of this dominant contribution to the mass of ordinary matter. The figure is taken from “Hadronic Signals of Deconfinement at RHIC,” B. Müller, Nucl. Phys.A750(2005)84.

A New Form of Matter Discovered at RHIC

What happens when a nucleus is heated to such extreme temperatures that neutrons and protons (nucleons) melt? The transformation of nucleons into a new state of matter consisting of liberated quarks and gluons is intimately related to the origins of mass, the behavior of matter in the early universe, and the structure of the vacuum itself. The investigation of this transition is a fundamental goal of nuclear science. At the time of the 2002 LRP, the initial operation of RHIC had just opened this new frontier.

Since then, the exploration of nuclear matter at RHIC’s ultra-high energy densities has proceeded with spectacular success. The RHIC experiments have established that temperatures of more than 2 trillion degrees are reached in the collisions of two gold nuclei, and they have demonstrated novel, partly unexpected properties of this new form of matter: it is far more opaque to quarks and, at the same time, a better flowing (i.e. lower viscosity) liquid than any matter known before.

RHIC was constructed to study the properties of matter under these extreme conditions, which existed during the first few moments of our universe, before the particles that make up atomic nuclei even existed. These particles, protons and neutrons, are known to be composed of quarks, which are "glued" together by gluons. But quarks and gluons are never observed alone in today's world. QCD relates this phenomenon to the very nature of the vacuum: what is ordinarily regarded as "empty" space instead possesses a complex substructure that, while allowing photons to propagate freely throughout the visible universe, prevents single gluons from traveling distances much larger than the diameter of a proton. QCD also predicts that the vacuum itself was different under the extreme conditions of the universe just after the big bang. At temperatures above 2 trillion degrees, the hidden structure of the vacuum is predicted to "melt" and assume a much simpler form in which gluons propagate more freely and quarks are liberated from their otherwise permanent confinement. The resulting state is called a "quark-gluon plasma." While the *existence* of such a state at ultra-high temperatures is theoretically predicted through extensive calculations on the most powerful computers, much less is known with certainty about its *properties*.

Today one can create the necessary conditions for temperature and density through collisions of large nuclei at high energies, as provided by RHIC. Four different detectors, BRAHMS, PHENIX, PHOBOS, and STAR, track and identify the thousands of particles produced in a collision of heavy nuclei (see **Fig. II-2**). The RHIC results to date clearly establish formation of a new kind of matter in collisions of heavy nuclei. The measured abundances of different kinds of produced particles, and their velocity distributions, are characteristic of a liquid in thermal and chemical equilibrium at the temperature where neutrons and protons are predicted to melt, and furthermore of a liquid with extremely low resistance to flowing motion. In fact, the matter produced in these collisions appears to be the least viscous liquid ever observed, approaching the limit for small viscosity, set by the laws of quantum mechanics. This observation has attracted great interest outside the nuclear physics community, because these properties have been predicted by theorists in certain models of the strong interaction closely related to QCD. Both the flow results and other data involving the relative yield of particles formed from three quarks and from quark-antiquark pairs suggest that quarks are indeed locally liberated in these collisions at RHIC and only recombine to form baryons and mesons when they try to leave the high-density matter.

Data for gold-gold nucleus collisions, when compared with critical calibration data measured at RHIC in proton-proton and deuteron-gold collisions, unambiguously establish the novel phenomenon of "jet quenching" (see **Fig. II-2**) resulting from the energy lost by energetic quarks and gluons propagating through the dense matter created in the collision of heavy nuclei. The magnitude of the observed quenching is even more impressive than anticipated: in head-on collisions, the remaining high-momentum particles appear to originate only from quarks or gluons scattered outward from a thin surface layer, while the sister quark or gluon that must burrow through the bulk of the matter in the opposite direction is highly suppressed. In the deformed hot zone produced in off-center collisions, the suppression is found to depend on the emission angle about the collision axis. This phenomenon opens up a novel diagnostic probe for the produced matter, aptly called "jet tomography." While this new form of matter appears nearly opaque to particles that feel the color force of QCD, recent measurements show that photons, which interact only electromagnetically, shine directly through the matter.

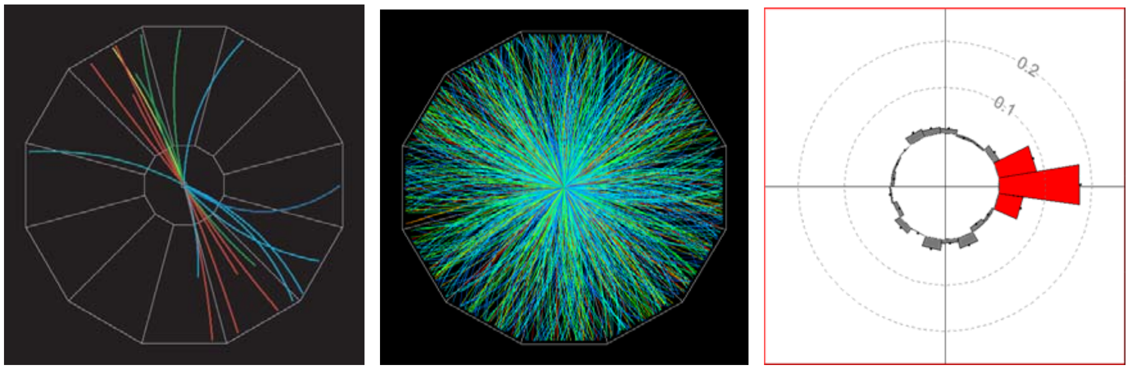

Figure II-2. STAR detector event displays for a typical proton-proton collision (left) and for a head-on collision of two gold nuclei (middle) at RHIC. Each colored line represents the track reconstructed with the detector for one charged particle produced in the collision. The straighter lines represent higher momentum particles. The left frame shows the characteristic pattern of a “di-jet” event resulting from the hard scattering of a quark or gluon in one proton from a quark or gluon in the other. RHIC experimenters have developed robust methods to sift through the remnants of heavy-nucleus disintegration (middle frame) in search of similar patterns of back-to-back nearly straight tracks. When they select events where at least one such track is found, the companion tracks on the opposite side appear to be missing, as shown by data from the PHENIX Collaboration in the rightmost frame. This strong suppression of di-jet patterns in head-on collisions of nuclei — a phenomenon called “jet quenching” — manifests the strong energy loss of quarks and gluons traversing the new form of hot, dense matter discovered at RHIC.

The large magnitude of the measured energy loss (at least 15 times the value measured for normal nuclear matter) and the inferred low resistance to flow both indicate that the matter created at RHIC is characterized by very strong interactions, much more so than was anticipated by theorists who expected rather weak interactions among quarks and gluons at temperatures high enough to liberate quarks. This fundamental discovery will direct much of the future research effort in relativistic heavy ions at RHIC. Here we frame that program as a series of questions, to be answered by the analysis of new data and by upgrades (discussed later in this section) to the detectors and the accelerator complex:

- *How low is the viscosity of the fluid created in RHIC collisions?* Answering this question will require data for different nuclei and beam energies and a careful study of how the flow is manifested in various particles, particularly those containing such heavy quarks as charm and bottom.

- *What is the speed of sound in the medium and its equation of state?* The RHIC experiments have revealed tantalizing hints of shock phenomena induced in the medium by passage of a high-energy particle. If confirmed, such phenomena would allow a measurement of the sound velocity, a fundamental property that provides a measure of the compressibility of condensed matter.

- *What mechanisms are responsible for the extremely rapid thermalization?* Novel theoretical ideas suggest that equilibration is driven by collective effects rather than particle collisions. Experiments will search for signals of such collective plasma instabilities by measuring the angular correlations between emitted particles.

- *What is the internal structure of the matter produced at RHIC?* Systematic measurements requiring very high beam intensities will probe the survival probabilities of various rare particles that consist of a heavy quark and antiquark bound together. These will tell us whether the matter is composed of liberated and independent quarks and gluons.

- *What is the nature of the QCD phase transition?* Experiments measuring the spectra of low-energy electrons will search for a change in the structure of the vacuum in which the primeval symmetry related to the mass of the quarks is restored.

- *Can the initial state be described as a "color glass condensate"?* The hypothesis that nuclei from helium to uranium, as well as protons and neutrons, at very high energy can be described as a collection of coherent gluon fields—similar to an ensemble of randomly oriented laser beams—is a fascinating novel idea that will be tested at RHIC.

These questions demonstrate the broad range of fundamental issues that have emerged from the RHIC discoveries to date and that drive a multi-pronged strategy to upgrade the RHIC facility over the next decade, as discussed later in this section.

Physics with High Energy Polarized Protons

RHIC has achieved a unique status as the world's first collider of polarized proton beams, i.e., beams where the spin directions of the colliding protons can be experimentally controlled. This capability enables a program to find the "missing" proton spin, thus addressing a central puzzle in our understanding of how nucleons are assembled from quarks and gluons.

Electron and muon beams from the world's highest-energy accelerator facilities have revealed that no more than half a proton's overall momentum can be accounted for by summing up the momenta of its charged constituents: the valence quarks and the sea of quarks and antiquarks. The remaining half of the momentum, as well as a major fraction of the mass, must then be attributed to the multitude of self-interacting gluons inside the proton. The gluons have thus come to be seen rather as majority "silent partners," not exerting open influence on the nucleon's quantum numbers, but giving the nucleon much of its real "clout."

Later experiments probing the proton and neutron with spin-polarized electron and muon beams revealed a similar, but even more striking puzzle: less than one-third of the nucleon's spin arises from the quark and antiquark spins within it. Does the remainder again arise from the gluons, through alignment of their intrinsic spins? Or does it rather arise from orbital motion of the quarks and gluons inside the nucleon? Solving the puzzle of the missing spin will illuminate the nature of the "sea" inside a proton containing many quark-antiquark pairs and gluons that contribute most of the proton's mass.

In order to address this question, the spin orientation of gluons in a spin-polarized proton (with spin oriented preferentially either along or opposite the momentum direction) must be probed directly. However, the gluons do not interact with the electron or muon probes that have proven so effective in mapping the quark distributions. Instead, directly probing the gluons requires the use of strongly interacting beams, but under conditions where the strong interaction itself is sufficiently well understood to permit clear extraction of information about the nucleon's internal structure. The best hope is to study hard scattering processes at high energies, where a quark or gluon inside one beam particle imparts a strong sideways kick to a counterpart inside a particle from the other beam. Such collisions are, in principle, cleanly interpretable in the framework of QCD with the aid of standard approximation techniques, taking advantage of the *asymptotic freedom* of the strong interaction, the feature for which the 2004 Nobel Prize in Physics was awarded. According to QCD, the spin sensitivity in such collisions is significant only when *both* interacting quarks or gluons have preferential spin orientations, so that a polarized collider is required to address the origin of the proton's missing spin. Such a capability was first demonstrated for proton beams at RHIC in 2002, representing a technological coup not likely to be duplicated at any other facility in the foreseeable future. Thus, RHIC is and will remain a unique facility worldwide for addressing the nucleon spin puzzle.

Initial physics results from proton-proton collisions at RHIC already reveal that QCD provides a good explanation of the reaction rates of greatest interest for probing gluon spin preferences. The first significant limits on these preferences are anticipated to result from the study of abundant reactions—the production of mesons and jets (as in **Fig. II-2**)—in the 2005 RHIC run. A more detailed map of the preferences as a function of a gluon's share of the proton's momentum will be made via the less abundant photon production reaction in subsequent runs. A full map requires measurements at both 200- and 500-GeV collision energy, the latter representing the maximum possible energy at RHIC.

At the highest collision energy, a second class of measurements becomes feasible. Here the production of the weak intermediate vector bosons W^+ and W^-—the mediators of the weak force responsible for nuclear radioactive decay—will be detected as a function of the spin orientations of the two proton beams. The W^+ is produced by the fusion of an *up* quark from one proton with an *antidown* quark from the other, while W^- results from a *down* + *antiup* fusion. By exploiting the mirror symmetry violation inherent in the weak interaction, these measurements can determine the spin orientation preferences directly for each of the four types of quarks involved. In particular, a clean measurement of the *difference* between *antiup* and *antidown* quark polarizations will provide a stringent test of models for the production of the quark-antiquark sea in a proton, and hence for the origin of mass.

Measurements providing complementary clues to proton structure will use proton beams prepared with their spins oriented perpendicular (transverse) to the momentum direction. These data probe the directional preferences for quarks and gluons moving perpendicular to the proton's direction, preferences connected to the possible internal orbital motion that might account for part of the missing proton spin. Early RHIC spin results have already fueled intense interest by demonstrating for the first time that large transverse spin sensitivity exists in proton collisions easily amenable to QCD treatment.

Definitive answers to the questions regarding the missing proton spin are possible within the next decade, provided the envisioned RHIC spin program of precision measurements is pursued. A natural follow-up stage to these basic investigations of the origin of nucleon spin would constitute a significant portion of the program at the planned high-energy electron-ion collider, eRHIC, described next.

Electron-Ion Collisions at RHIC

In the framework of QCD, the unique and intriguing properties of all strongly interacting systems—what sets them dramatically apart from atoms and molecules—arise from the interaction of gluons with other gluons. The complexities normally associated with this self-interaction are predicted to evolve toward a simple unifying behavior in the limit of very high gluon density. One can explore this regime by probing the abundant gluons that individually carry a very small fraction (less than a tenth of one percent) of the momentum of their parent nucleons or nuclei. Lepton scattering can precisely probe the electrically neutral gluons by using the fundamental aspect of QCD that quarks and gluons are intimately connected in a known way. In the limit of very high gluon density, rates for processes where two gluons fuse to become one gluon are comparable to rates for single gluons splitting into two gluons, leading to a saturation of the gluon density. Therefore, when high energy beams probe the low momentum components of any nucleon or nucleus, they will interact not with individual gluons, but with a coherent gluon field with properties universal to all strongly interacting matter—the so-called color glass condensate. The intellectual challenge of searching for such universal behavior and testing QCD in this largely unexplored territory is one of the new scientific opportunities driving an electron-ion collider upgrade for RHIC.

The 2003 NSAC Subcommittee on the Twenty Year Nuclear Physics Scientific Horizon and the 2004 DOE Office of Science Strategic Plan have each endorsed a high luminosity electron-ion collider having both polarized nucleon and heavy ion beams, as the leading candidate for the next-generation (beyond the energy-doubled CEBAF) facility to study QCD. Such a facility would extend the QCD precision frontier currently explored by polarized deep inelastic electron scattering, a technique with a spectacular record of success. To date, experiments exploiting this process with high-energy electron or muon beams have provided the first direct evidence for the quark structure of protons; the first inferences of the crucial role of gluons in accounting for proton mass and momentum; the establishment of the “missing” proton spin issue; and stringent tests of QCD predictions for how the quark structure of the proton evolves with the strength of the kick imparted by the electron to the struck quark. The availability of heavy ion beams at an electron-ion collider is of critical importance, since cooperative contributions to the gluon field from the many nucleons in a heavy nucleus could then be explored. These multiple contributions would allow physicists to study the anticipated gluon saturation regime at much lower energies than would otherwise be required.

In the last several years, a realistic and cost-effective technical design for such a collider has been developed, utilizing the existing RHIC accelerators. This electron-ion collider, known as eRHIC, would optimally begin operation near the conclusion of the ongoing RHIC program with its focus on the recently discovered new state of hot, dense matter and the measurement of the proton spin structure in proton-proton collisions.

eRHIC will make possible precise measurements of fundamental aspects of the structure of the nucleon and atomic nuclei in this gluon-dominated regime, at energies where QCD calculations can be directly confronted. Among the fundamental issues to be addressed are:

- precisely mapping the distribution of low-momentum gluons in nuclei, to see if the anticipated universal features are encountered;

- extending the study of the contributions to the overall spin of protons and neutrons to the abundant—but currently inaccessible—sea quarks and gluons that each carry less than 1% of the nucleon momentum;

- dramatically improving the precision of experimental tests of a fundamental QCD relationship between the spin structures of the proton and neutron.

eRHIC is the natural next-generation facility to extend the precision study of QCD matter into previously inaccessible domains. While its implementation is clearly beyond the time scope of the present report, it represents an important part of a long-range vision for U.S. nuclear science research leadership. The scientific opportunities that accompany this vision may well be lost to the field if RHIC operations were to be seriously curtailed or terminated in the near future. The high-energy polarized proton and heavy-ion collider beam capabilities that are already mature at RHIC offer a unique opportunity to realize such a facility in a cost effective manner, and would open a window of precision investigation of new QCD phenomena in nucleons and nuclei.

B. Science at Jefferson Laboratory

Overview

One of the grand challenges in science today is to decipher the interconnections among natural phenomena that occur at enormously different length and time scales. The breadth of these phenomena is vast, ranging from the quarks that are the infinitesimal building blocks of protons and neutrons and the gluons that cement the blocks together, to the cosmos at its earliest microseconds, and to the universe as it exists today. The CEBAF accelerator at Jefferson Laboratory is a unique facility for studying a crucial aspect of this vast undertaking: cold nucleonic matter—the stuff that forms the core of the atoms of which the stars, the earth, and human life itself is made.

The CEBAF facility provides intense, continuous beams of energetic electrons, making it a giant electron microscope that probes into the heart of this strongly interacting, nucleonic matter. The electron beams are remarkably versatile: they can be spin polarized, their energy can be varied, and they can be focused with surgical precision on a variety of different targets. By performing a series of select experiments with this precise and powerful instrument, CEBAF physicists are mapping out the way in which quarks and gluons combine to form protons and neutrons and are gathering deeper insight on how protons and neutrons unite to form light nuclei. With a cost-effective and strategic energy doubling—the 12-GeV Upgrade—CEBAF will be poised to greatly improve and expand on studies of nucleon structure, and it will launch entirely new research directions associated with searches for exotic hadrons and physics beyond the standard model.

What is the internal structure of the proton and neutron and where does its mass and spin come from? A highlight of the early results from CEBAF was a surprise found from a precision map of the quark distributions in space: the distributions of electric charge and magnetism were found to be different. Extending this work, novel approaches using parity-violating electron scattering made it possible to measure strange sea quarks arising from the QCD vacuum. The higher energy that will come with the 12-GeV Upgrade will make it possible for the first time to build a dynamical map of quark distributions combined in position and momentum. These new distributions will form a comprehensive map of the quark and gluon structure of the nucleon and will help to answer questions such as: how much of the proton spin is generated by quark orbital motion?

What are the possible new species of particles that can be formed from quarks and gluons? Quarks and gluons are the basic building blocks that form all observed strongly-interacting particles—the hadrons. But only hadrons made from three quarks—the baryons, e.g., the proton and neutron—and those made from a quark and an antiquark—the mesons, e.g., pions and kaons—have been shown to exist. The rules of QCD make no such restrictions. Indeed, QCD allows many other quark and gluon combinations to form, such as four-quark states, five-quark states, states made only of glue—glueballs, and states made of a quark, antiquark and a gluon—hybrids. Where are these exotic hadrons? Do they exist at all? Can discovery of exotic hadrons elucidate our present understanding of how quarks combine; that is, can they provide insight into how the confinement mechanism works? These are important questions and the upgraded

CEBAF program will include a new Hall and large-scale detector capable of testing the QCD predictions with unprecedented sensitivity. If hybrids exist, the GlueX experiment at CEBAF will find them.

What is the new physics that lies beyond the standard model? This question is generally directed to high-energy physicists; they hope to answer it at the LHC at CERN by producing very massive particles predicted by theories beyond the standard model. However, insight and discovery can come from a high-precision, lower-energy facility. CEBAF, even at 6 GeV and especially with the 12-GeV Upgrade, has a unique sensitivity to new physics through quantum effects, in the same way that the high-energy facilities BaBar and Belle search for evidence of beyond-standard-model physics such as supersymmetry. For example, in parity-violating electron scattering, the weak charges of the quarks can be measured with unprecedented precision, and effects due to new physics could be unambiguously detected.

Finally, **Jefferson Lab is a superb facility for addressing novel aspects of physics of nuclei.** For example, by knocking out a neutron in He-3, one can study directly the correlated motion of the two protons in the original nucleus. By measuring the electromagnetic form factors of a nucleon in a nucleus, one can study possible changes in the charge and magnetization distributions of individual nucleons in a nuclear environment. Finally, high-precision measurements of the apparent "neutron skin" of a heavy nucleus can be made through a parity-violating experiment, and the result will be important for understanding the physics of neutron stars.

Science at 6 GeV and with the 12-GeV Upgrade

Many studies carried out with CEBAF are aimed at detailed understanding—several experiments are needed to examine different aspects of a problem, and each yields a piece of the answer. This requires both flexibility in the experimental tools and the ability to quickly respond to new opportunities, while continuing to exploit existing programs and plan for the longer term. The description of the physics in the following sections is not a comprehensive representation of the CEBAF 6-GeV program or that of the 12-GeV Upgrade program, but rather an attempt to capture both the broad nature of the science and the steady evolution from the present to the future.

Structure of the nucleon

Protons and neutrons are described by the microscopic theory of quarks and gluons, QCD. However, the dynamics of QCD are so complex that we cannot make reliable calculations of nucleon structure at present. **What is the internal landscape of the proton?** To understand the properties of the nucleon, we must map the complete position and momentum distributions of quarks and gluons through experiments. This effort began in the mid-1950s with the first crude measurements of the elastic scattering of high-energy electrons from protons, continued through the1970s, and thrives today. These experiments first taught us that the proton has substructure, they elucidated this substructure, and eventually they showed us that what we first thought was true about this substructure was wrong. For example, only in recent years have we learned, via the spin dependence of electron scattering from aligned nucleons, that the quark spin actually contributes very little to the spin of the nucleon. Despite these important results, the information we have gathered so far provides only a sketchy outline of the full picture.

The simplest probe of the nucleon's structure is elastic electron scattering, which measures the probability that the nucleon remains whole after absorbing a photon. Elastic scattering can be accurately predicted if the nucleon had no internal structure. Observed deviations from these predictions provided some of the early hints that some internal structure of the nucleon existed. Today, the observed deviations—described by form factors—can be used to determine the spatial charge and current distributions of the nucleon. Recent CEBAF results using this technique have shown that the spatial distributions of electric charge and magnetization in the proton are significantly different from each other. The implications of these surprising differences will be explored further in new experiments at energies up to 11 GeV that will test theoretical explanations of the early data.

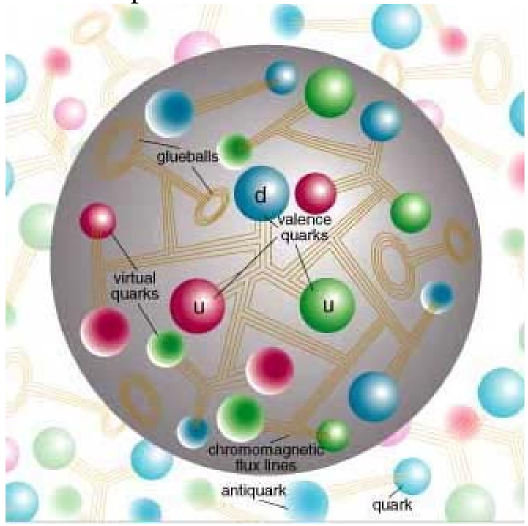

Figure II-3. The internal structure of the proton showing the three valence quarks that are usually thought of as making up the proton as well as the sea of virtual quarks, antiquarks and gluons. It is this sea—generated by QCD—that is responsible for most of the mass and spin of the proton.

While much of what we know about the structure of the nucleon in early years has been learned from elastic electron-proton scattering, this technique does not tell us how fast the quarks are moving or how much momentum and energy they carry. A second approach to mapping the quark and gluon structure of the nucleon is to study deep-inelastic scattering (DIS), a process in which the electron is scattered from individual quarks within the nucleon, knocking them out and destroying the original nucleon. A DIS experiment measures the momentum distributions of the quarks in the nucleon and thus provides information that is complementary to the elastic scattering form factors. The measurements have shown that in protons and neutrons, “virtual” quark-antiquark pairs continually pop in and out of what is called the “sea” and may be thought of as a kind of bubbling in the fabric of the space-time vacuum.

Valence Quarks

From the results of many years of DIS experiments, we now know that the virtual quark-antiquark pairs and gluons arising from the sea account for the bulk of the mass of a proton and neutron. However, we normally picture protons and neutrons as being made of three quarks called “valence quarks.” In probing nucleon structure using electron scattering, it is important to do experiments in which the scattering is dominated by valence quarks and not by the virtual particles and the glue. In this so-called valence region, the structure is simpler and lends itself to quantitative prediction. Mapping out the behavior of the valence quarks would be a powerful step in unraveling the way protons and neutrons are built out of quarks and glue, but this valence region is almost out of reach with existing facilities.

With the 12-GeV Upgrade, CEBAF will become the ideal facility for studying valence quarks. One of the requirements is high beam intensity, something that CEBAF already offers. Another important aspect is that the electrons have sufficient energy to be reasonably certain of scattering from a single quark. At 6 GeV, CEBAF's electron energy is just barely high enough. However, at 12 GeV, it is possible to do scattering where the valence quarks dominate. Using unpolarized electrons and unpolarized targets, it will be possible—for the first time, to distinguish unambiguously between the various predictions for the way in which the "up" and "down" quarks are distributed. By using polarized electrons and polarized targets, it will be possible to glean information regarding the way in which the spin of the proton and neutron is carried by the underlying quarks and gluons. The "spin structure" is a powerful check of our understanding of subatomic matter and has already given important hints of its ability to distinguish between different descriptions of quarks and gluons. At 12 GeV, we will finally be able to pin down important features of the behavior of the valence quarks. In doing so, we will be opening a new door in a quantitative study of the structure of the nucleon in terms of QCD.

Parity as a Probe of the Strange Quark Sea

We now know that the quark-antiquark pairs and gluons from the sea account for 90 percent of the mass of the nucleon. However, the virtual character of the quark-antiquark pairs means that they cannot contribute to properties such as overall charge. They can, however, contribute to the *local* charge distribution, as long as the net charge arising from virtual particles, averaged over the entire nucleon, is zero. Thus, strange quarks—not normally thought of as being a part of a nucleon—can contribute to the nucleon properties by modifying the distribution of electrical charge and magnetism in a nontrivial manner.

In traditional electron scattering experiments, any effects arising from strange quarks are mixed with the larger effects of the dominant up and down quarks. A program of parity-violation experiments carried out at CEBAF is able to separate these effects. Using polarized electrons and unpolarized targets, these very precise experiments look for tiny differences when an initial experimental configuration is switched to its mirror-image. It is as if one looks for a tiny difference in the physical laws between this world and the "looking-glass world" in Lewis Carroll's *Alice in Wonderland*. These differences occur because of the "weak force." The earliest parity-violation experiments looked at radioactive decay and were done to study physics related to the weak force. The electron scattering parity experiments have been progressively refined to the point that they can be used to probe some of the subtlest aspects of the nucleon, with CEBAF now hosting the most sensitive experiments to date. Results from CEBAF combined with the earlier world data have greatly constrained the degree to which strange quarks contribute to the static properties of the proton and neutron. A striking very recent CEBAF result is that the sum of the strange quark's contribution to electric and magnetic form factors—the charge and current—is at least 5 percent of the total, a result that is much larger than most expectations. CEBAF experiments expected to run in the near future will be able to separate the two form factors and allow us to understand the important role that strange quarks seem to be playing in defining the distributions of electric charge and magnetization in the nucleus

Generalized Parton Distributions

To determine how quark angular momentum contributes to the spin of the proton, we must know where quarks are and how they move. A novel approach has been developed and tested at CEBAF. The feasibility studies demonstrate that we can indeed measure quark position and momentum "maps" that will lead to determining the angular momentum component of the proton spin. The classic experimental techniques—elastic and deep-inelastic electron scattering—yield the distributions of the constituents separately in space or momentum, respectively. But, this is an incomplete picture as it does not describe the correlations between the position and momentum of the quarks and gluons. In the last few years, striking theoretical progress has been made in identifying novel experiments that can be used to probe quarks in position and momentum simultaneously—the resulting maps are called generalized parton distributions (GPDs).

Theoretical distributions for combined position and momentum can be introduced naturally for quarks and gluons in the nucleon. Given this joint distribution, the three-dimensional orbital motion of quarks in the proton can then be studied. This in turn can determine what the contribution of the quark's angular momentum is to the spin of the proton. These joint distributions, GPDs, can be turned into observable quantities that are combinations of elastic form factors and momentum distributions. Project a GPD in one way and you get a form factor. Project it in another way and you get a momentum distribution. With enough information one can build up a dynamical image of the proton in a manner similar to tomography. The image offers unprecedented possibilities for visualizing the proton through quarks with selected momentum. CEBAF has begun to probe GPDs in the last few years through electron scattering on the proton, observing production of photons and mesons. To make a detailed measurement of GPDs requires a full systematic experimental program at a facility having high luminosity and energy. CEBAF, with the 12-GeV Upgrade, will offer the first such opportunity.

Exotic Particles and QCD

The picture of nucleons and mesons as either three-quark or quark-antiquark objects and the early spectroscopic data that supported this view was a key piece of science that led to the acceptance of QCD as the theory of the strong interaction. However, even though this picture described the particles that were observed in nature, our understanding of QCD led us to believe that there might well be quark configurations beyond the simplest that we had observed—so-called exotics. It also became clear that while in QCD gluons are responsible for confining the quarks together, gluons do not appear necessary to describe the particles that we observe. While careful searches for exotic particles have been carried out at many facilities, the current evidence for exotics either suffers from a clear separation from normal particles, or is limited by low statistics where a clean separation is possible. The question "**Where is the glue that binds quarks into strongly interacting particles and what are its properties?"** remains an open one in QCD. Positive evidence of exotics and a detailed mapping of their properties will provide critical information about the inner workings of QCD. An opportunity to answer this question is at hand with the 12-GeV Upgrade.

The GlueX Experiment and Hybrid Mesons

A unique feature of QCD is the idea that quarks and gluons are trapped within the particles of which they are the constituents, but a quantitative understanding of the confinement mechanism still eludes us. While we believe that the gluons play a crucial role in this mechanism, direct experimental signatures for the role of glue have been difficult to find. Recent theoretical progress using computer calculations from first principles (e.g., lattice QCD) indicates the existence of a new family of exotic particles, "hybrid mesons," in which the role of the gluons can be more readily observed. Experimental information about hybrids will be an essential ingredient of the ultimate understanding of the confinement mechanism.

While the gluons of QCD play a similar role to that of light in electromagnetism, they are fundamentally different. They interact not only with the quarks, but also with each other, a situation that would arise if light carried electric charge as well as energy. Because of the interaction between gluons, they can be confined to a small, narrow region of space between the quarks, and it is predicted that matter containing only gluons should exist. The trapping of the gluons also creates a large force (many tons) that holds the quarks together. The gluons not only hold the quarks together, but also can collectively move and contribute more than just mass. The simplest such motion is a rotation much like that of a jump rope. This jump-rope motion is believed to be responsible for the exotic particles, while the masses of these particles are related to the energy in the rotation. Thus detailed information on the masses of hybrids will provide information on the confining gluon field.

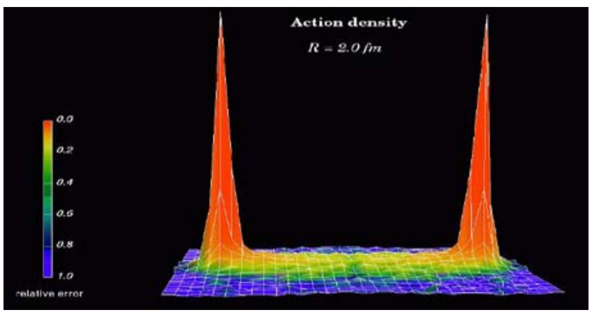

Figure II-4. A lattice-QCD calculation showing the density of color charge around a heavy quark-antiquark pair. The two spikes correspond to the location of the quark and the antiquark, and the region in between shows the trapping of the color charge.

An energy-doubled CEBAF provides a new and unique way to access exotic hybrids using beams of high-energy spin-polarized light. Complementing CEBAF with the proper apparatus and preparation, it will be possible to carry out a complete search with hundreds of times the sensitivity of all previous efforts. This opportunity has led to the formation of an international team of about 100 experimenters and theorists to pursue the search. The GlueX Experiment has been designed and optimized to both find and carefully measure properties of the exotic particles. By sifting through enormous data sets, carrying out multi-pronged analyses, and directly integrating theoretical input into the process, GlueX will explore the existence of the exotic particles and provide the crucial measurements that are expected to help unravel the mechanism of quark confinement. This program can only be carried out at an energy upgraded CEBAF.

Pentaquarks

In 2003, experimental results hinted at a completely new form of matter, the pentaquark. As a bound state of four quarks and an antiquark, it differed from all other known particles. While broad symmetry principles allow for such quark combinations, there are no solid theoretical predictions that pentaquarks should exist. Thus a confirmed observation would be particularly exciting. Several experimental collaborations around the world, including one at CEBAF, analyzed existing data and found low-statistics signals that appeared to confirm the original announcement. These observations were greeted with both great excitement and deep skepticism and spawned hundreds of papers trying to explain this unexpected finding. If the pentaquark exists, it would create a whole new field of study and challenge our understanding of how quarks build up protons and neutrons. Confirming this result, and, if true, verifying the properties of this particle, became a priority.

Over the next year, more experimental groups looked carefully at their existing data, but saw no signal. Without a careful dedicated measurement, however, a definitive answer would be elusive. Jefferson Lab quickly responded to the opportunity. Several experiments having different sensitivities were approved, and new data were collected within a year of the announcement. A large effort went into improving precision and analysis tools, all with the goal of making a definitive statement. The resulting careful analysis of the high-statistics data has yielded a crucial negative result, already presented this spring, less than a year after the data collection was complete. While this result casts strong doubt on the existence of pentaquarks, the ability to quickly respond to future opportunities that challenge our view of QCD remains an exciting part of the future of the CEBAF program.

Symmetry Tests with Electrons

The quest to uncover new symmetries involving the elementary particles—quarks and leptons (electrons, muons, taus and their neutrinos)—in the early universe is an important part of the nuclear physics mission. The standard model of the electroweak and strong interactions has provided a remarkably successful account of the interactions involving protons and neutrons and leptons in processes studied thus far in laboratory experiments. Yet we suspect that the standard model provides only an incomplete account of the forces between leptons and quarks. We expect these forces to exhibit new patterns of behavior—or symmetries—when studied at high energies or short distances. High-energy collider experiments search for these new forces by probing the energy frontier, while experiments in nuclear physics rely on ultra-precise measurements to search for deviations from standard-model-based expectations at short distances.

One approach that can be uniquely pursued at Jefferson Lab is to study the weak interactions of electrons with matter and with themselves at high precision. Experimentally, nuclear physicists can separate the effects of the weak interaction from those of the much stronger electromagnetic interaction by exploiting the violation of the "parity" symmetry that only happens for the weak force. As discussed above, this parity-violating effect in electron scattering from nucleons and nuclei has been used to study the strange quark sea inside the nucleon—in effect, exploiting the parity-violation of the weak force to probe a distinctive part of the QCD map of the nucleon. Because that effort has been so successful, nuclear physicists are now poised to use the same idea—but with even higher precision and different experimental conditions—to study the nature of the weak interaction at short distances and look for evidence of new forces and symmetries beyond those of the standard model.

The power of this probe comes, in part, from the special character of the standard model weak force between electrons and quarks and between electrons and other electrons. The particle that carries this force—the Z^0 boson—is actually a mixture of two "primordial" force carriers, and the strength of the Z^0 interaction with quarks and leptons is determined by the degree of this weak mixing. Moreover, the extent of mixing depends on the distance scale at which the weak force is observed. There are indications that the standard model prediction is not fulfilled by experiment, particularly with respect to data obtained recently at Fermilab. New experiments at CEBAF, including measurements of parity-violation in elastic electron-proton scattering at the 6-GeV facility, inelastic electron-deuteron scattering using the 6- and 12-GeV beams, and electron-

electron scattering at 12 GeV will probe the distance dependence of the weak interaction strength in a regime that cannot be accessed by high-energy colliders, but for which the standard model makes a well-defined and theoretically unambiguous prediction. To date, less than a handful of experiments, such as the pioneering parity-violating electron-electron scattering experiment just completed at SLAC, have studied this dependence.

Importantly, the standard model prediction for weak mixing in this domain implies that the parity-violating interaction of the electron with the proton and between electrons themselves is small. Consequently, these measurements are particularly transparent to the effects of new forces and symmetries at short distances. Moreover, the comparison of results of different parity-violation experiments with other precise symmetry tests carried out in nuclear physics offers a unique diagnostic tool for discerning what new forces are most likely to be active at short distances, higher energies, and earlier times in the universe. These forces could include interactions generated by a symmetry called “supersymmetry” or by more massive analogues of the Z^0 and W bosons of the standard model.

A Future at CEBAF---Electron-Light-Ion Collider

A future upgrade of CEBAF beyond 12 GeV would build on the physics insights obtained from the 12-GeV Upgrade, and expand on our understanding of the structure of the nucleon and nuclear binding. Studies by Jefferson Lab users and by physicists associated with the Electron Laboratory for Europe (ELFE) project have established that there is a strong physics case for the construction of an extremely high luminosity ($\sim 10^{38}$ cm^{-2} s^{-1}) CEBAF-like accelerator with energies in the 20-30 GeV range. A strong physics case is also developing for an electron-light ion collider (ELIC) operating in the 20-65 GeV center-of-mass energy range. Some of the outstanding physics issues driving this higher-energy and higher luminosity upgrades include:

- **Direct measurement of quark wave functions through exclusive processes: h**igh-energy exclusive scattering is a special class of collisions in which the final product involves creation of only a few particles, a rare type of processes. QCD study of exclusive processes show that they can probe directly components of the quark wave functions of hadrons involved.

- **Quark and gluon structure of the nuclei:** quark and gluon structure of nuclei are known to be very different from that of free protons and neutrons, particularly when quarks and gluons carry either a large or small fraction of the momentum of a nucleus. However, a detailed knowledge of this difference is still uncertain at present. Probing this difference is crucial to understanding the limit to which a nuclei may be considered as a system of protons and neutrons.

As noted in the NSAC 2002 Long Range Plan, *“many of the outstanding scientific opportunities that have been identified …. require the higher beam energies that will be provided by the CEBAF 12-GeV Upgrade, which should take place at the earliest opportunity. In the longer term, an Electron-Ion Collider has been put forward as the next major facility for this field. This is an exciting proposal for which the scientific case will be refined in the next few years. In* *parallel, it is essential that the necessary accelerator R&D be pursued now, to ensure that the optimum technical design is chosen."*

Conclusion

After decades of careful planning by the nuclear science community, followed by major investments by the nation, the U.S. now has the world's preeminent electron accelerator facility: the CEBAF facility, whose research program helps educate a third of the nation's PhDs in nuclear science, hosts researchers from nearly every state and many nations and attracts strong foreign investment in support of its programs. By combining precision, high-intensity, highly polarized electron beams with a suite of cutting-edge detectors and experiments, researchers are able to use a well-understood probe to study how quarks and gluons make up the protons and neutrons in the world around us. The outstanding scientific opportunities now demand that the energy of CEBAF be doubled to maintain its unique position in the exploration of the rich variety of fundamental hadronic phenomena.

C. Other Opportunities for QCD Studies

The world class facilities of JLab and the RHIC spin program have no peers internationally in their respective areas, electromagnetic studies of QCD structure of hadrons and nuclei and measurements of the fraction of the spin carried by the gluons, respectively. However the nuclear science community has very effectively taken advantage of focused opportunities at facilities worldwide to complement these measurements with unique probes targeted at specific physics issues. Many excellent examples can be noted: for example recent results include the measurements of the HERMES experiment at DESY of the flavor dependence of the spin carried by the individual flavors of quarks, evidence for new classes of quark distributions (the transverse spin distribution discussed on page 19), and how the process by which quarks turn into the particles we observe changes inside nuclei and hadronization in the nuclear medium; the SLAC E158 measurement of parity violation in electron-electron scattering to search for physics beyond the standard model; and BNL and KEK measurements of double-strange nuclei.

Such experiments are essential to capitalize on the scientific discoveries of our major facilities, prepare the way for new U.S. initiatives, and address outstanding physics issues beyond the primary capabilities of the U.S. facilities. Moreover, they are extremely cost effective, usually relying on non-U.S.-nuclear-physics sources of primary operating costs, and often major international funding of experimental equipment. In the next decade exciting new opportunities have emerged, often associated with major investments worldwide.

The new capabilities of high intensity 120 GeV proton beams at the FNAL main injector can be exploited in an approved experiment (E906) to definitively measure the flavor dependence of the antiquark sea of the nucleon, finally resolve the 20 year old question of the expected nuclear dependence of the antiquark distributions (Where are the nuclear pions?) and set precise limits on quark energy loss in cold nuclear matter. To date, programs at the main injector have been limited by the focus on maximizing the sensitivity for collisions at the highest energy, but as the LHC comes on line, additional experimental thrusts can likely be undertaken. Experiments could also capitalize on the intense neutrino beams at FNAL produced for neutrino oscillation experiments to investigate QCD physics such as the strange quark contributions to the spin of the nucleon, nucleon weak form factors, the flavor and nuclear dependence of parton distributions (especially the strange and antistrange distributions) as well as provide new measurements of neutrino nucleus cross sections.

The high power proton accelerator, Japan Proton Accelerator Complex (JPARC) and the FAIR project at GSI will open new windows of opportunity for U.S. nuclear scientists. These two new facilities and their potential science programs are discussed below in Section III.

D. The Physics of Nuclei and Nuclear Astrophysics

Overview

How are nuclei assembled from their fundamental building blocks and interactions? How do complex systems exhibit such astonishing simplicities and regularities? How many elements and nuclei are yet to be discovered? How can we understand the origin of the elements and the nuclear reactions that drive stars? How can nuclei best be exploited for the benefit of mankind and the security of our nation? These are among the questions that nuclear scientists seek to answer. And the answers affect science over a distance scale of more than 40 orders of magnitude—from the proton (10^{-15} m) to the universe (10^{25} m).

The elementary building blocks of the nuclei in our *everyday world* are the protons and neutrons that are bound together via the strong interaction. Understanding the nucleus is a complex quantum many-body problem of incredible richness and diversity that shares common themes and challenges with much of modern science, ranging from the biosphere and nanoscience to the physics of the cosmos. **Figure II-3** illustrates some of these connections. Beyond the concepts, there is a sharing of tools and techniques that further connect researchers in our discipline to colleagues in the many-body condensed-matter community on the one hand, and astrophysicists who work to understand stellar evolution on the other.

How are nuclei assembled from their fundamental building blocks and interactions? How do complex systems exhibit such astonishing simplicities and regularities? How many elements and nuclei are yet to be discovered?

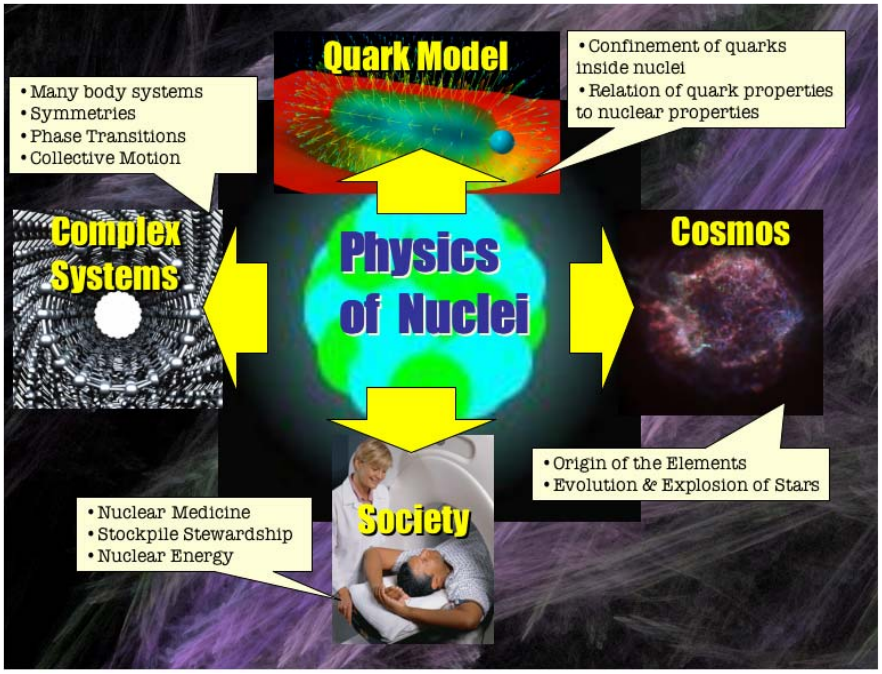

Figure II-3. The physics of nuclei forms the intellectual bridge between the very large and the very small in our natural world.

These first three questions for the field focus on the microscopic theory of nuclei. Nuclear scientists strive to derive the properties of atomic nuclei from the interactions of protons and neutrons, or ultimately, from quarks and gluons. Indeed, nuclei are *the only link* between QCD and the atomic and macroscopic world. This approach—starting from basic components to create a complex system—is a common one in science and is shared by chemists and materials scientists, whose building blocks are atoms and molecules, and biologists and biophysicists, who work with large macromolecules like proteins that make up cells and complex organisms built on their constituent cells and molecules.

Nuclear properties often display striking regularities—such as energy levels that mirror nearly perfect rotational motion—which point to the purity of particular quantum states. Likewise, nuclei display structural changes with neutron and proton number; sometimes these changes are abrupt, sometimes gradual. Understanding these regularities in terms of symmetries of the many-body system, and their breaking, as well as in a microscopic framework, is a truly challenging problem. Deficiencies in our present understanding have surfaced as we study nuclei that have vastly different ratios of protons to neutrons compared with stable nuclei. Today, we have limited knowledge of just how many neutrons can be added to a stable nucleus before it becomes unable to hold more. We need new theoretical and experimental tools to make progress in the future.

How can we understand the origin of the elements and the nuclear reactions that drive stars? The fourth question underscores the truly cosmic implications of nuclear processes. Stars are amazing macroscopic systems whose ability to shine and evolve over time is driven by nuclear physics. Stars are nature's grandest alchemists, wherein sequences of thermonuclear reactions transmute one element to another and, as a result, convert tiny amounts of matter to enormous amounts of energy. Stars have a lifecycle, with some fizzling out after billions of years while others catastrophically annihilate in the most violent explosions known. Stellar debris from such celestial fireworks populates successive generations of stellar systems and constitutes the elements of which we and our world are made. This is the realm of nuclear astrophysics, an interdisciplinary field that addresses how physics on the length scale of subatomic nuclei can drive astrophysical phenomena 10^{24} times larger. The otherworldly aspect of this field captivates both the general public and research scientists. We may know that we are made of stardust, but we do not know which type of stars synthesized our atoms. For this reason, and because we need to decipher the spectacular discoveries by the Hubble and other space telescopes, work in this field is exciting, timely, and important.

How can nuclei best be exploited for the benefit of mankind and the security of our nation? The last question reveals that studies of nuclei benefit mankind in many ways. For example, they provide a wealth of isotopes and nuclear techniques for medical applications (both diagnostic and therapeutic), industrial applications, and national security and defense. One out of every three people admitted to a U.S. hospital benefits from advances in nuclear medicine, that are firmly rooted in basic research in low-energy nuclear physics laboratories. Many of the procedures utilize microscopic-size quantities of radioactive isotopes for the diagnosis of cancer, Alzheimer's disease, heart disease, and other life-threatening medical conditions. This roughly $10B-a-year industry produces specialized subatomic nuclei that are used for hundreds of thousands of medical procedures each day across the U.S. Currently research focuses on developing new applications of and more efficient production processes for known isotopes. Clearly, the potential impact of discovering a new isotope for nuclear medicine is enormous.

Nuclear science's impact extends beyond healthcare. One of the answers to the nation's energy problem lies in nuclear power. The technological wizardry to make this happen requires a thorough understanding of both nuclei and their reactions. In numerous applications, such as stockpile stewardship, nuclear waste disposal, reactor design, satellite power, and environmental science, low-energy nuclear science plays a vital role in techniques and equipment development, and training of the next generation of scientists who will have the ability to exploit nuclei for the benefit of mankind and the security of the U.S.

Given the extraordinary societal implications and the impact on science, it is amazing that technical limitations have prevented all but a fraction of subatomic nuclei from ever being studied in the laboratory. Fortunately, today, with revolutionary technological advances, we are poised to qualitatively advance our understanding of the atomic nucleus and the role played by nuclei in the cosmos. Here, the study of rare isotopes, in particular with the Rare Isotope Accelerator, RIA, will lead the way by providing access to a vast, uncharted landscape of unstable nuclei. Because of the far-reaching impact of low-energy nuclear physics on science and society, RIA represents an intelligent, strategic investment in the future of our nation.

The Physics of Nuclei: Present and Future Science

What binds protons and neutrons into stable nuclei and rare isotopes?

Intricate internal nuclear forces, which have yet to be completely determined, and two different species (protons and neutrons) generate a range and diversity of behavior that make the nucleus a truly unique object. For decades, nuclear scientists have used data-inspired models that embody various properties of the nucleus. However, we still lack a full, microscopic understanding of the nucleus. We do not know the mechanism of nuclear binding precisely enough to tell what nuclei can exist in nature. Nor do we know the properties of short-lived nuclei that control the evolution of the cosmos. Fusion and fission are phenomena that were discovered in the early years of nuclear science, but our description of these fundamental nuclear processes is still very inadequate. Better understanding of them is needed for many applications, including nuclear power reactors to produce energy for the nation; models of energy production in stars; future fusion power sources; stockpile stewardship and nuclear weapons programs for the nation's defense; and nuclear non-proliferation, which is a central concern for Homeland Security. For nuclear science to achieve its potential to benefit society, we will need a deeper understanding of nuclei, their reactions, and their decay processes.

The ultimate goal of the field is to develop a unified, predictive theory of the nucleus and of nuclear matter, such as that found in the crust of neutron stars. Through the influx of new ideas and progress in computer technology and numerical techniques, we have made qualitative changes to the way we do nuclear modeling. A roadmap has been developed. We have a clear, well-controlled theoretical path that bridges light nuclei—which can be calculated precisely in terms of protons and neutrons interacting via inter-nucleon forces—with medium-mass nuclei and with complex heavy and superheavy species. Of course, how well this roadmap serves us, and what modifications to it will be needed, will be determined by the new data made possible by advanced instruments in the years to come.

The current, limited exploration of exotic, short-lived nuclei having large neutron-to-proton imbalance has shown a wealth of new physics and has demonstrated that the “universal” ideas of nuclear properties are in fact not correct. **Figure II-4** illustrates how unusual these new forms of nuclei can be compared to nuclei studied so far. The new data send us a clear signal that the theoretical models that we apply to nuclei near stability are only reflections of a more general and far richer theory. What is it about exotic nuclei that will provide new information in the quest for a deeper understanding of nuclei? They are likely to provide a wealth of new and unexpected phenomena. And they will provide us with a much larger “gene” pool of nuclei that will give us individual laboratories to *amplify and isolate* particular properties and nuclear interactions that are not evident in stable systems, but are essential to a fundamental understanding of how nuclei are assembled.

Light nuclei are a proving ground for nuclear scientists probing inter-nucleon forces. The helium atom with two extra neutrons added, is the simplest nuclear system having a two-neutron *halo*: two loosely bound neutrons that orbit around a compact core (illustrated for the case of an isotope of lithium—lithium-11—in **Fig. II-4**). This nucleus lives for about 1 s—long enough for nearly 10^{20} orbits of the constituent nucleons. But take away one neutron or the alpha particle and the system will immediately fall apart. The two extra neutrons interact together—a pairing interaction—to make this system of an alpha particle (helium-4) and two neutrons stable. Pairing is a common, yet not understood feature of nuclei. It is the same phenomenon that is responsible for superconductivity in heavy nuclei. Recently the charge radius of this exotic form of helium was measured with high accuracy by trapping the exotic atoms. The results represent a stringent test of calculations and provide new information on the poorly known three-nucleon “tidal” force. Such halo nuclei will also provide new insights in to the origin and nature of pairing in nuclei, provided we can find examples in heavier nuclei. RIA will provide such examples up to mass 100, ten times larger than those currently studied.

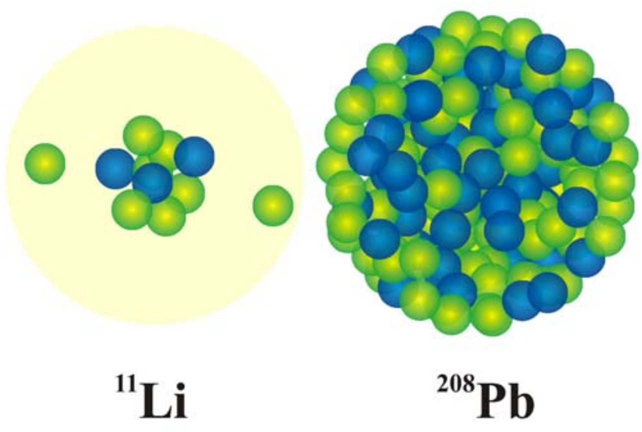

Figure II-4. Rare isotopes can have exotic features that provide new insight into the study of nuclei. This figure is a scale illustration of the size of the orbits of weakly bound neutrons in the heaviest, rare lithium isotope, compared with the size of a lead nucleus. The figure illustrates that standard assumptions, such as that the size of a nucleus depends only on the total number of neutrons and protons, are not always valid.

Heavier neutron-rich nuclei may develop *neutron skins* that will dramatically affect their structure, reactions, and decays. This effect can have important consequences in the astrophysical r process (a sequence of neutron capture reactions on unstable nuclei that is thought to synthesize half of the elements heavier than iron in supernovae). The available intensities at

RIA will allow study of nuclei having a neutron skin thickness six times larger than those now available.

The properties of neutron-rich nuclei are crucial to our understanding of neutron stars. The crust of a neutron star may have a crystalline, “pasta”-like structure, made of nuclei. Because of the lack of a reliable inter-nucleon interaction, the specific structure and properties of the crust are known only qualitatively at best. Measurements of the properties of neutron-rich nuclei, of neutron skins, and of neutron and proton radii made possible by RIA may have important implications for deciphering neutron-star properties from their cooling rates and possible gravitational wave emission, thus helping us build a bridge between finite nuclei and bulk nucleonic matter.

Nuclei, in particularly tightly bound isotopes, find arrangements regarded as "magic." Such nuclei are reminiscent of noble gases that behave as inert gases, because their closed electron shells are so stable and un-reactive, However, increasing evidence indicates that nuclear magic numbers, the cornerstones of our understanding of nuclear structure, are strongly dependent on the neutron-to-proton asymmetry and nuclear binding energy. Some magic numbers have disappeared in neutron-rich systems, and new ones have been found. RIA is the ideal tool to study this shell structure for very exotic nuclei, because it provides the full range of isotopes necessary to elucidate this behavior, akin to having a full DNA sequence rather than a DNA fragment.

Is the nucleus hard to squeeze? The answer is given by the nuclear matter equation of state (EOS) that describes the possibility of compressing nuclear matter. It plays a central role in nuclear structure and heavy ion collisions, and it determines the static and dynamical behavior of stars, especially in supernova explosions and in neutron star stability and evolution. Recently, using different experimental approaches, the compressibility parameter—a critical element of the EOS—has been deduced. In nuclear collisions at RIA, a transient state of nuclear matter having an appreciable neutron-to-proton asymmetry and large density can be created, offering the unique opportunity to study the neutron number dependence of the EOS, which is crucial to understand supernovae.

What are the limits of atoms and nuclei?
Much of the discovery potential of RIA will focus on finding just how many neutrons can be added to an element before it falls apart. An important aspect of this is answering the question: how heavy can atomic nuclei be? Making superheavy nuclei has long been an important step toward answering fundamental questions about matter and the universe, but it has not been easy. One of the goals of our research is to reach the region of superheavy elements with around 112 protons and 184 neutrons. Nuclei from this region are expected to live longer than a year, and their atoms have unusual chemical properties arising from the relativistic motion of the atomic electrons. However, no target-projectile combination of stable isotopes will directly lead to this region. Thus, nuclear scientists are turning to unstable, radioactive nuclei. In a recent experiment, an unstable beam of tin nuclei was smashed into a stable target of nickel. The rate of low-energy reactions was about 10 times higher than that observed with a stable tin beam having fewer neutrons. The new results raise the prospect that intense neutron-rich radioactive beams, in combination with neutron-rich radioactive targets, may produce the most neutron-rich

nuclei of heavy actinides, transactinides, and, ultimately, superheavy elements. Besides providing information about nuclear structure, that strategy might lead to novel radioisotopes for medicine, improved understanding of nuclear-weapon behavior, and insights into astrophysical phenomena such as supernovae.

Simplicity from Complexity

Complex systems often display astonishing simplicities, such as sequences of states with nearly perfectly spaced energies. Nuclei are no exception; they often function as highly ordered systems. Examples of such regular behavior abound. In hundreds of nuclei having even numbers of protons and neutrons, the ratio of the energies of the lowest two excited states is often almost exactly 3 1/3. Why? The answer may lie in the behavior of complex systems when certain symmetries exist. Symmetries tell us that nuclei have lost their perfectly spherical shapes and behave like rapidly rotating footballs. It is astonishing indeed that a heavy nucleus, consisting of hundreds of protons and neutrons roaming around within the nuclear volume, can exhibit a *collective motion*, in which all particles dance in unison. How is this possible? The origin of many-body symmetries is a challenge that microscopic theory tries to explain.

Why do nuclear symmetries exist? When are they are broken? When are they enhanced? Insight can be gained by the study of phase transitions—such as that which occurs when water freezes. Such a transition takes place when the shape of a complex nucleus radically changes by adding just two protons or neutrons. Moreover, just like ice and water, phases can coexist in the *critical point*; certain nuclei can exist in more than one shape! This surprising effect has recently been observed, for example, in samarium and has been described with a new concept of “critical point” symmetries. The insight from this one example sparks the drive to discover more. RIA, with its access to extended sequences of new nuclei, will make crucial regions of coexistence available for investigation. For example, at RIA, neutron-rich isotopes of zirconium, krypton, and barium, which are all candidates for critical point symmetries, will be available with sufficient intensities to be studied.

An object or phenomenon is said to be chiral if it is not identical to its mirror image, regardless of how it is viewed. Chirality is important in many fields, including biology, physics, and chemistry. Handedness of molecular shapes, discovered by Pasteur in the 1840s, is a common example of this phenomenon. However, it was not suspected until recently that nuclei could also exhibit a chirality of a new kind associated with proton and neutron angular momenta, rather than geometric shapes. This prediction has been confirmed with experiments at Gammasphere. To further understand chirality in nuclei, study of a few key specific examples in rare isotopes is necessary.

At low temperatures, nuclei are superconductors. Attractive nuclear interactions can lead to a phenomenon of pairing, in which nucleons are coupled in pairs, very much like electron Cooper pairs in metals. However, unlike metals, nuclei are relatively small systems in which surface effects can add new complications. Non-spherical pairing fields, later identified in high-T_c superconductivity, are common in nuclei. Our concept of pairing in nuclei is undergoing a revolution as a result of insights from light nuclei with large neutron excess. The challenge for the future is to understand novel pairing phases in neutron-rich nuclei (strongly influenced by a neutron-to-proton imbalance) and a deuteron-like pairing in proton-rich nuclei that is carried by proton-neutron pairs having their spins aligned in the same direction. With RIA, proton-neutron pairing can be studied in proton-rich nuclei with equal numbers of protons and neutrons, up to the heaviest bound cases around ^{100}Sn (50 protons and 50 neutrons).

Nuclear Astrophysics

Studying Nuclei in the Cosmos

Nuclear science plays a crucial role in understanding stars, galaxies, and other cosmic phenomena. Studies of these systems hinge on sophisticated computer simulations that encode astrophysical theories and attempt to explain the latest observations from the Hubble and other telescopes. These simulations require, as input, enormous amounts of nuclear physics information—the properties of (in some cases) thousands of nuclei and their interaction rates. Because incomplete and uncertain nuclear physics information limits the reliability of the predictions of many astrophysical simulations, our understanding of the cosmos will not advance without progress in nuclear science.

How do we make headway? All required nuclear information will never be measured, so simulations are consulted to determine which measurements are most critical. In some cases, nuclear reaction and structure models are invaluable as they must provide *all* of the required unmeasured nuclear properties. In others, direct measurements must be performed. Eventually all of the information must be catalogued in a form that makes it available for the stellar modeler. The highly synergistic nature of this interdisciplinary field requires *simultaneous investments* in manpower and new facilities for laboratory measurements and in manpower for theoretical calculations and information handling.

Progress in our field is driven in part by fascinating new astronomical discoveries. In recent years two brand new types of stellar explosions have been found—X-ray “superbursts” and an as-yet-unnamed outburst on a star in the Milky Way.. Nuclear physics input is needed to explain these phenomena. Our field is also driven by the development of new research tools—accelerators, beams, calculations, simulations. Both stable and rare isotope beams are needed to provide nuclear physics input into unraveling the diverse phenomena found in the cosmos. The nuclear astrophysics community has identified one major facility, RIA, as their ultimate goal for rare isotope beams because of its unrivalled capabilities in the *extreme* frontier of the field—studies of stellar explosions with radioactive beams.

Exploding Stars and Radioactive Beams

When stars explode, the temperatures and densities are so high that unstable nuclei can be formed by a nuclear reaction and then undergo additional reactions before they decay. To study the nuclear properties and interactions that drive these explosions, beams of radioactive nuclei are essential. The highest priority in this work is to understand the r process, a sequence of neutron capture reactions on unstable nuclei that is thought to synthesize half of the elements heavier than iron. The structure and reactions of the thousands of exotic nuclei involved is so uncertain that we cannot discriminate between different r-process simulations to determine the relevant temperatures and densities. We do not know whether the process occurs in supernovae, merging neutron stars, or some other exotic cosmic location. Recent observations even suggest the possibility of *two distinct* r processes. Astronomers are planning to observe tens of thousands of stars in the galactic halo searching for trace heavy element abundances, and the international scientific world will be looking to nuclear physics to decipher the results of these high-priority observations. Clearly this area is of prime importance to our field.

Simulations of heavy-element production suggest that the reactions involving nuclei with the "magic numbers" of 50, 82, and 126 neutrons can significantly affect the number of elements synthesized in a stellar explosion. In the last few years, new radioactive beam capabilities have resulted in some initial progress in understanding nuclei having 50 neutrons. The first measurement of the lifetime of the nickel r-process nucleus having 28 protons and 50 neutrons was recently made. The new result points to a faster cosmic synthesis of heavy elements than was previously assumed from theoretical estimates. Another recent result used reaccelerated beams of radioactive germanium and selenium, both r-process isotopes having 50 neutrons, to "simulate" an r-process neutron capture reaction. Results from these measurements will be used to calculate new capture reaction rates and modify predictions of heavy-element stellar burning. But this is just a start. In the longer term, solving the r-process puzzle cannot be done without orders-of-magnitude increases in beam intensities of as many exotic nuclei as possible.

The U.S. has gained and maintained leadership in this science. Through effective utilization of our existing facilities and modest upgrades, this prominence can be maintained for the next few years. But new facilities (e.g., RIKEN in Japan, GSI-FAIR in Germany) will soon turn on. To stay competitive, the U.S. needs RIA—it will constitute *the* future enabling technology for r-process work. While other international facilities will address some targeted r-process measurements, only RIA will have the capability to produce the nuclei farthest from stability that best test nuclear models. Moreover, RIA will allow detailed studies of the properties of these nuclei that are poorly understood today.

Radioactive beams having an excess of protons also are required to understand explosions in binary star systems, such as novae and X-ray bursts. Here, a sequence of rapid proton capture reactions, the rp process, powers these rapacious outbursts, which result from a star's consuming hydrogen-rich material transferred from a companion star. This displaced material erupts in a giant thermonuclear outburst on the surface of a tiny white dwarf star or a neutron star. Since almost all of the relevant nuclear reactions are currently estimates from theory, understanding these extraordinary events requires measurements of the most important proton capture reactions and decay lifetimes. Recent simulations suggest that the X-ray burst luminosity can be drastically altered by changing one of the thousands of input reaction rates. A few specific reactions that are crucial for these explosions have recently been nailed down by direct measurements with radioactive beams and "indirect" studies using stable beams, but these account for only a fraction of the required information. However, without RIA, numerous fundamental questions about these explosions—such as which reactions trigger them, how hot they get, and how much mass they eject—will not be answered.

Bizarre Properties of Neutron Stars

While destroying one star, a supernova simultaneously signals the birth of a new one—a neutron star or a black hole, two of the most exotic objects in all of the cosmos. The first remnant is primarily composed of neutrons, weighs more than our sun, but at only 20 km across is smaller than the center of many cities. These stars are thought to have a complex, incredibly dense, multi-layer structure, 18 orders of magnitude larger than nuclei, yet sharing common features with specific exotic nuclei. As we noted, the neutron star crust may in fact have a crystalline structure composed entirely of nuclei. Understanding this phenomenon will require RIA. As stellar material is "burned" in the atmosphere of the neutron star, creating a flash of X-rays, the heavy ashes fall onto the surface and are converted from iron and tin to lighter nuclei by a series of nuclear interactions and decays. This process is likely the source of the newly observed "superbursts." Moreover, any asymmetry in the burning process could be a potential source of gravitational wave emission in rapidly rotating neutron stars. To understand all of these phenomena, we must measure the rates of electron capture on heavy nuclei, and we need better atomic masses and electron capture rates for neutron rich iron isotopes. All of the relevant masses and most of these rates can be measured at RIA. If the relevant nuclear data can be constrained, then precision X-ray observations (and possible future detection of gravitational wave emission) can provide confirmation of these and even more exotic processes on neutron stars.

Simmering Stars: The Low–Energy Frontier

In addition to their crucial role in stellar explosions, charged-particle-induced reactions cause stars such as our Sun to shine and chemically evolve in time. Because the yields of these reactions are so low at temperatures where stars simmer instead of explode, it is common to measure them at higher energies in the laboratory—where the yields are higher—and then extrapolate the results to lower energies. However, these extrapolations are difficult and, in some cases, have very large uncertainties. Recently, a direct measurement was made at stellar energies of the proton capture on stable nitrogen, consistent with one measurement at higher energies and one indirect measurement at very high energies. The new results lower the previously accepted reaction rate by a factor of 2, changing the estimate of the age of stars in globular clusters by about 1 Gyr. This is but one example of possible problems with existing measurements. A new frontier in nuclear astrophysics—to measure these reactions at the lowest possible energies to avoid or minimize such extrapolations—is emerging. This work requires a laboratory having a high-current accelerator and state-of-the-art detection systems that are shielded from cosmic rays. Such an underground laboratory, modestly equipped is operating at Gran Sasso in Italy. Constructing a major facility of this type in the U.S. at an underground laboratory would reduce the background from cosmic ray interactions by orders of magnitude, compared with similar measurements obtained at current U.S. facilities, enabling measurements that are impossible today. Such a modern lab would establish the U.S. as an international leader in direct low-energy measurements of thermonuclear reactions in non-exploding stars.

The Future

Near-term progress in the study of nuclei and nuclear astrophysics will depend on continued use of existing facilities and collaboration between nuclear scientists, astrophysical modelers, and computer scientists. Two DOE user facilities, ATLAS at ANL and HRIBF at ORNL, the NSF-user facility NSCL at MSU, and university laboratories can provide researchers with a wide array of stable beams and some rare isotope beams. NSF initiatives such as the Joint Institute for Nuclear Astrophysics, JINA, Physics Frontiers Center provides a critical link between nuclear science and astrophysics. Upgrades now underway at HRIBF and one of the university laboratories, Texas A&M University, will expand the range of rare isotope beams. But to remain competitive in the near term, we must provide the nuclear structure and astrophysics community with running time at our existing facilities and additional facility and detector upgrades. The community will also continue to exploit opportunities outside of the U.S. at ISAC, RIKEN, GSI, and GANIL.

Current facilities with modest upgrades will have a 5–10 year window to continue forefront science. While our existing first-generation radioactive-beam facilities and stable-beam facilities will provide exceptional targeted opportunities, the future of the program lies with RIA. This unique world-leading facility will be an unprecedented tool for probing the science questions that concern nuclei and nuclei in the cosmos. RIA will provide access to key nuclei, especially those farthest from stability; it will provide necessary data for theory to develop the comprehensive model of the nucleus as well as for astrophysics; it will attract and train young nuclear scientists; and it will provide data relevant to many other fields and applications that will benefit society and our nation. Constructing RIA and nurturing its 1000-scientist-strong community will ensure U.S. leadership in low-energy nuclear science for decades to come.

E. Neutrinos and Fundamental Symmetries

Neutrinos are the most elusive particles in nature; they are almost impossible to catch and extremely difficult to observe. Yet they carry many of the secrets to the evolution of the universe, the burning of stars, and the creation of the heavy elements. Neutrinos can be created using man-made accelerators, but they also pour out harmlessly from all nuclear power reactors. They rain down on Earth directly from our own Sun and from the interactions of cosmic rays in the upper atmosphere. In the past few years, nuclear physicists have developed large underground experiments—designed to detect a tiny fraction of the passing neutrinos—and have collected enough information to ignite a "neutrino revolution." We now know with certainty that neutrinos have mass and that they continuously flip-flop back and forth between different types (called "flavors").

However, we do not yet know the full story required to re-write the physics textbooks; we now know only that our old understanding was woefully wrong. The neutrino measurement program outlined below should complete the story, perhaps with an ending that may reveal even more surprises. It is a program of high priority across many sub-fields of physics.

The enormously successful standard model represents our current understanding of the fundamental building blocks of the universe: quarks and leptons; and how they interact: through the exchange of gauge bosons. The model is arguably one of the most impressive in scientific history, but physicists have long been troubled by its large number of parameters and have suspected it is but an approximation of a more comprehensive theory. With the discovery of neutrino mass, we have for the first time seen physics beyond the standard model. The model is undergoing unprecedented scrutiny now in a series of experimental tests we term "fundamental symmetry" measurements. Nuclear physicists are playing central roles in many high-precision theoretical and experimental efforts that have already begun to hint at other cracks in the standard model. The standard model is incomplete; the select program described below has the sensitivity to find out why.

Neutrino Physics

More than 70 years after it was proposed, the neutrino's elusive properties are finally coming to light. The combination of solar, atmospheric, reactor, and accelerator data reveals that neutrinos can change flavor by undergoing "oscillations" and shows that at least two neutrino types have nonzero, distinct masses. This simple fact has forced us to modify the standard model of particle physics for the first time since it was created more than 30 years ago. There are three neutrinos, having masses m_1, m_2 and m_3, and oscillation experiments give the differences between the squares of the masses, which may be expressed as Δm_{12}^2, Δm_{13}^2, and Δm_{23}^2. Any two difference pairs, sign and magnitude, are sufficient to fix the third. From the experiments conducted to date, we understand that m_1 and m_2 are quite close in mass, with m_1 the lighter of the pair. We also know that the mass of m_3 is rather different from either m_1 or m_2, but we don't know if it is lighter or heavier than the pair. The expected or "normal" neutrino hierarchy has m_1 and m_2 light and m_3 heavy, but an "inverted" pattern is equally possible, whereby m_3 would be lighter than m_1 and m_2. In addition to the three mass-squared differences, three mixing angles are needed to describe the fraction of each flavor (electron, mu, and tau) contained in each neutrino mass state.

One of these angles has been determined by studies of the solar and reactor neutrinos and one by studies of atmospheric neutrinos. The third mixing angle has not been measured, but it is known to be small.

In addition to measuring the properties of the neutrino, we have also entered the age of neutrino astronomy, where we use neutrinos as a unique probe of the universe around us. In 2002, the third Nobel Prize for neutrino physics was awarded to Davis and Koshiba for detecting neutrinos from the Sun and from supernova 1987a. These measurements confirmed our basic picture of the Sun: it shines due to the release of energy from nuclear fusion. They also confirmed our basic understanding that a supernova results from a stellar collapse to nuclear density with the majority of the gravitational energy being released in the form of neutrinos.

Since 2002, nuclear science has made the following advances in neutrino physics:

- The Sudbury Neutrino Observatory (SNO, **Figure X**) has provided definitive evidence for the flavor change of solar neutrinos, by detecting the appearance of mu- or tau-type neutrinos
- SNO has also made the second step in solar neutrino astronomy, going beyond the basic detection of solar neutrinos, by validating the theoretical determination of the solar neutrino flux.
- The Kamioka Liquid scintillator AntiNeutrino Detector (KamLAND) has demonstrated reactor antineutrino disappearance and made the most precise measurements of Δm^2_{12}. The results agree with solar neutrino experiments and confirm that the degree of mixing between the species of neutrinos involved in solar processes is large, but less than what is maximally possible.
- KamLAND has observed the shape distortion in the reactor antineutrino spectrum, as predicted by neutrino oscillation theory.

The SNO and KamLAND results complement each other in a spectacular fashion. The oscillations of neutrinos coming from the Sun are strongly affected by matter, while those involving reactor neutrinos are dominated by vacuum oscillations. Two different phenomena predicted by the neutrino mixing theory, and which depend on the same two parameters, have been experimentally confirmed.

The recent discoveries raise important and clearly defined questions that can be answered by new experiments. These new experiments will be difficult, but they can be realized.

Basic Questions and Scientific Approaches

What are the masses of the neutrinos? The mass of the neutrino is experimentally accessible through single beta decay experiments, neutrinoless double beta decay experiments, neutrino oscillation measurements, and cosmology. From oscillations, we can set a lower limit on the average neutrino mass of 20 meV. Tritium beta decay sets an upper limit of 2.2 eV. A more restrictive, but model-dependent, upper limit is deduced from studies of the large scale structure of the universe combined with observations of the cosmic microwave background radiation, which indicate that the neutrino mass is less than 0.5 eV (about half a billionth of the mass of a proton). Even at the lower limit, 20 meV, neutrinos contribute as much mass to the universe as do stars. Direct mass measurements can tell us whether neutrino mass is, in fact, large enough to influence the large scale structure of the universe.

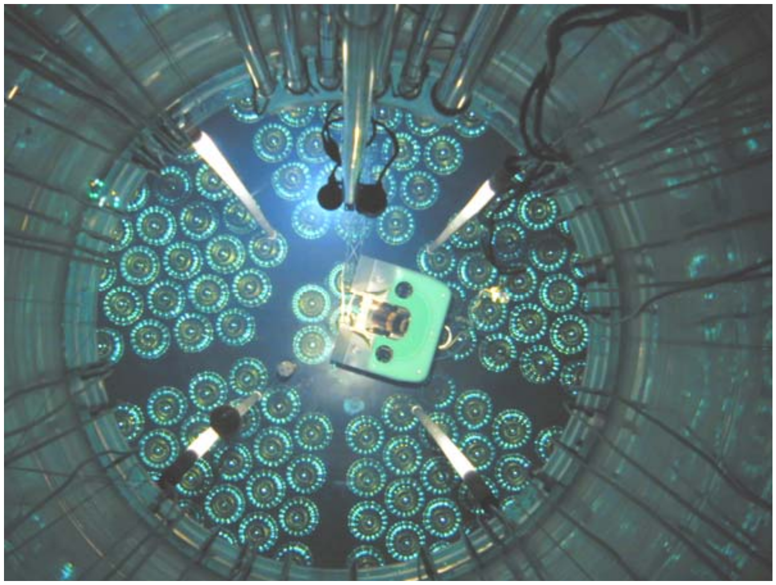

Figure II-7. Looking down the neck of the Sudbury Neutrino Observatory at the heavy water, with some photomultipliers 23 m below. The green object is the submersible vehicle used to deploy an array of ^{3}He proportional counters, of which four can be seen.

Are neutrinos and antineutrinos the same particle? Neutrinoless double beta decay occurs only if neutrinos are "Majorana" (i.e., neutrinos and antineutrinos are the *same* particle). The rate of this very rare decay mode depends on the mass hierarchy described above and on the mixing angles. For example, in the "inverted" mass hierarchy scenario, neutrinoless double beta decay could occur often enough to be established in early versions of new experiments. On the other hand, if neutrinos exist in a normal hierarchy, the experiments will have to be scaled up in size, and the observation period will likely extend beyond 2015. The discovery of neutrinoless double beta decay would guide the construction of the fundamental theory of matter. Experiments with several isotopes will be required to confirm this important result and to determine the value of the Majorana neutrino mass precisely.

What is the pattern of mixing among the various types of neutrinos? Were neutrinos partly responsible for the matter-antimatter asymmetry of the universe? The unknown third mixing angle mentioned above enters into a surprising array of important questions in physics and astrophysics. Measuring this mixing angle is thus a major target for neutrino physics, and experiments at nuclear reactors are being designed to measure it directly by means of neutrino oscillations. It appears in combination with other parameters (the mass hierarchy) in accelerator-based measurements, and a coordinated program can ultimately determine all three. The value of the angle is needed to interpret a future supernova neutrino signal, and to develop a better understanding of the core temperature and explosion mechanism. The angle must also be known (and non-zero) in order to be able to observe the violation of the symmetry CP (charge-parity: reflect in a mirror and change matter to antimatter). Understanding whether neutrinos violate CP is not only necessary for building the new theory of matter, it may also offer an explanation of why the visible universe contains matter but essentially no antimatter.

Do "sterile" neutrinos exist? A startling signal, seen by the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos in the mid '90s, suggested the existence of a relatively heavy neutrino that cannot be accommodated in a world that has only three neutrino flavors. Could this be some type of "sterile" neutrino, that is, one that exists but evades conventional detection? This type of heavy, special, neutrino—if it exists—is important because it could create a viable environment for producing the heavy elements in supernovae. The MiniBooNe experiment at Fermilab will soon confirm or refute the LSND signal.

What can neutrinos disclose about the deep interior of astrophysical objects? Neutrino-nucleus interactions in a nascent supernova are an important but poorly understood influence on the synthesis of elements in the supernova, and the reverse process of electron capture on nuclei is a determining factor in the explosion dynamics. Once neutrinos from a supernova have reached the Earth, they are detected through neutrino-nucleus interactions. An experimental program to determine the important unknown neutrino-nucleus cross sections is now possible using the copious neutrino flux from the Spallation Neutron Source (SNS). The solar neutrino spectrum at higher energies has provided fundamental information about neutrino properties and confirmation of the standard solar model. Measurement of the solar neutrino spectrum at low energies would provide a direct and detailed test of our understanding of solar physics.

Near Term Opportunities:
In response to the rapidly developing knowledge of neutrinos and its applicability in many different fields, four divisions of the APS recently completed a study of the opportunities and made a number of recommendations. The present Department of Energy Nuclear Physics funding for neutrino physics supports three running experiments: SNO, MiniBooNe, and KamLAND. It also supports R&D for a tritium end-point measurement (KATRIN), neutrinoless double beta decay and low-energy solar neutrinos. The National Science Foundation supports construction of the Borexino low-energy solar neutrino experiment. As the APS study emphasizes, it is essential to complete the programs in which investments have already been made. Specifically this involves:

1. The SNO neutral current detector program must be completed to provide the most precise determination of the mixing angle θ_{12}.
2. The Borexino experiment should begin operation and will provide the first spectroscopic determination of the flux of the low-energy ^{7}Be neutrinos.
3. The KamLAND reactor experiment must be completed to strengthen the case of the shape distortion of the spectra and improve the precision on Δm_{12}^2 by a factor of 2.
4. Completing the MiniBooNe neutrino run and analyzing the data will confirm or refute the LSND claim, which is not consistent with a basic three-flavor mixing scenario.
5. KATRIN, the neutrinoless double beta decay, and precision reactor neutrino experiments should make the transition to full experimental programs.

Future Opportunities

The APS neutrino study considered future opportunities and made the following recommendations:

1. We recommend as a high priority that a phased program of sensitive searches for neutrinoless double beta decay be initiated as soon as possible.
2. We recommend as a high priority a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos. This program should have the following components: a) An expeditiously deployed multidetector reactor experiment with sensitivity to disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits, b) A timely accelerator experiment with comparable $\sin^2 2\theta_{13}$ sensitivity and sensitivity to the mass hierarchy through matter effects, and c) a proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision.
3. We recommend the development of a spectroscopic solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary *pp* fusion process in the Sun.

The APS study furthermore emphasizes the importance of:

1. Underground laboratory facilities. Double beta decay and solar neutrino research must be carried out deep underground in appropriately designed laboratories
2. Determination of the neutrino reaction and production cross sections, required for precise understanding of neutrino oscillation physics and the neutrino astronomy of astrophysical and cosmological sources.
3. Research and development to assure the practical and timely realization of accelerator and detector technologies critical to the recommended program.
4. International cooperation. The opportunities for the U.S. outlined here make unique contributions to the international effort that will not be duplicated elsewhere.

Research in neutrino physics has been supported by both nuclear physics and particle physics. Solar neutrino experiments and direct mass measurements have been within the purview of nuclear physics. Most accelerator experiments have been supported by particle physics. Double beta decay and reactor experiments such as KamLAND have been supported by both. This indicates the cross-cutting nature of the field, and we expect this interdisciplinary flavor to continue. Neutrino astronomy began in nuclear physics with the detection of neutrinos from the Sun, and since that time many other disciplines have joined, such as particle physics, astronomy and astrophysics, and cosmology.

By studying the fundamental symmetries obeyed by nucleons, leptons, and their interactions, nuclear physicists are working to develop a unique window into the physics of the early universe. The basic method involves precise measurements of particle properties, which are compared to standard model predictions. The properties might include how a particle decays or how its spin wobbles (precesses) in a magnetic field. A significant difference between experiment and theory is a “smoking gun” for new physics—the type that may have had profound implications in the evolution of the universe shortly following the big bang. Fundamental symmetry tests—incorporating the experimental and theoretical tools in which nuclear physicists are experts—complement the information gained in high-energy collider experiments. The physics probed with precise symmetry tests can come from regimes beyond even those accessible at the most powerful high-energy accelerators in the world.

The accomplishments since the 2002 LRP have been significant, and the potential for future discovery is high. In what follows, we highlight three areas, each distinguished by very different techniques and findings. In each section, we review recent highlights and future directions.

Fundamental Physics with Neutrons

The neutron provides a marvelous laboratory for the study of the weak interaction and for tests of the standard model. For decades, the most intense source of low-energy neutrons was the ILL reactor in Grenoble, France. As a result, European groups have led the field for a long time. The situation is now changing with U.S. investment in experiments at the National Institute of Standards and Technology (NIST) and at the Los Alamos Neutron Science Center (LANSCE). The 2003 NSAC *Subcommittee on Fundamental Physics with Neutrons* endorsed the importance of this science and recommended development of a world-leading facility at the Spallation Neutron Source (SNS). Accordingly, new cold and ultra-cold neutron beam lines are being constructed. They will provide intense neutron beams appropriate for high-precision measurements. Thus, a highlight of the post-LRP period is the preparation of the new SNS facility and the buildup of U.S. expertise with first-generation experiments at NIST and LANSCE.

One of the most compelling opportunities in neutron science addresses why there is more matter than antimatter in the universe. We know that some kind of CP violation process is required to make this so. Although measurements with particles containing strange and bottom quarks have demonstrated that CP symmetry is violated by the weak interaction, the magnitude of the violation cannot account for the observed matter asymmetry. Perhaps CP is violated in the strong interaction among the light quarks or by the presence of new, but unobserved forces not contained in the standard model. A sensitive test of these possibilities is to look for a difference in the precession rate of a neutron placed in a magnetic and electric field when the electric field is oriented “up” or “down.” The rate can be different only if the neutron has a significant electric dipole moment (EDM), that is, a CP-violating preferred arrangement of the quark charges inside the neutron. A new search for a neutron EDM at the SNS—in tandem with parallel searches involving neutral atoms, electrons, muons, and deuterium ions to be performed elsewhere—will be sensitive to this additional CP violation at levels needed to explain the matter excess. If no EDM is found in these experiments, then CP violation involving neutrinos, as mentioned earlier, might offer another avenue for explaining the origin of the matter excess.

A new U.S. neutron EDM collaboration has carried out a research and development program, including construction and prototyping of key components, all aimed at a 500-fold improvement in the measurement sensitivity compared with the present world average. The ingenious new experiment would use the new SNS ultra-cold beam line and feature a new method to trap, spinpolarize, and measure the neutrons. The collaboration has met several key technical milestones, opening a clear path to beginning construction of the experiment in 2007.

While bound neutrons in stable nuclei do not decay, a free neutron will decay to a proton, an electron and an electron antineutrino in the process known as beta decay. The lifetime of the neutron—and the spatial distribution of the electron, antineutrino, and proton produced by its decay—provides an additional window on new forces at short distances. In the standard model, the decaying quark in the neutron and the emitted electrons are solely "left-handed", meaning that the relative orientation of their momenta and spins can be pictured by the following simple exercise: Point your left thumb along the direction of the electron and the natural curl of your left-hand's fingers gives the sense of the electron spin. This is how nature has constructed the weak interaction; however, it has long been thought that if the decay is viewed with sufficiently high precision, the quarks and electrons might also look "right-handed" some of the time. New precise measurements of the neutron lifetime and decay distributions—when compared with the lifetime of the muon—will search for these right-handed interactions with unprecedented sensitivity. Deviations from the standard model predictions for these measurements could also signal the presence of an additional family of quarks or of forces associated with a new symmetry known as "supersymmetry" (SUSY) that many physicists believe must have been present in the early universe. A recent theoretical accomplishment has been the computation of possible SUSY effects in the decay of the neutron and muon.. Additional theoretical efforts are aimed at ever-more-precise computations of the standard model predictions. Both provide very valuable guidance to the experimental program, which includes new efforts at NIST, LANSCE, and the SNS to determine the neutron lifetime and the decay distributions to very high precision.

Precision Muon Physics

One of the triumphs of the standard model has been a remarkably precise and accurate prediction for the magnetic moment of the muon (a heavy cousin to the electron). Indeed, the standard model predicts that the muon's magnetic moment should differ from the value predicted by Dirac, and the standard model expectation for this difference—known as the "anomalous" magnetic moment—has been confirmed over time by many elegant experiments. Recently, however, the BNL E821 Collaboration has performed the most precise measurement ever of the muon anomalous magnetic moment and has uncovered a potentially significant deviation from the standard model prediction. The results have sparked considerable excitement and hundreds of theoretical papers, because the most natural explanation of the deviation in terms of new forces would involve SUSY. While the finding is tantalizing, additional work is required before any discovery of physics beyond the standard model can be claimed. In particular, further refinements of the standard model prediction—involving scrutiny of contributions made by strongly-interacting light quarks—are underway in order to reassess the standard model prediction. In parallel to these efforts, new experimental ideas promise to increase the data collection at BNL tenfold. Together, the experiment-theory comparison should be definitive.

Like the neutron, the muon is unstable, and detailed studies of its decay products can provide important information about new forces at short distances. The TWIST Collaboration at TRIUMF has reported two new measurements of the so-called "Michel parameters" that describe muon decay in its most general form. Their results for these parameters have uncertainties nearly three times smaller than those obtained from previous measurements, and both results agree well with the standard model. Such agreement places stringent constraints on the possible existence of new interactions involving right-handed weak interactions.

The future frontier of precision muon physics also includes the NSF-sponsored MECO experiment at BNL, which will search for the conversion of muons into electrons in the vicinity of a nucleus. Such conversion is strictly forbidden by the standard model but it is expected in many candidate theories that go beyond it. The MECO experiment would provide one of the most powerful probes of new forces at short distances, as it would be sensitive to such effects at distance scales where the electromagnetic, weak, and strong forces are expected to merge into a single unified interaction. While the MECO effort is largely in the purview of high-energy physics, several nuclear physics groups are playing pivotal roles in its development.

Weak Mixing

In the standard model theory, the particle that mediates the weak force responsible for the decay of neutrons and muons is the massive, charged *W* boson (the *W* is about 80 times more massive than the proton). The *W* has an electrically neutral heavy partner called the *Z,* and because the *Z* carries no electric charge, it mediates the so-called "neutral weak force." The standard model assumes that the *Z* is actually a mixture of two more "primordial" force carriers and that the amount of this mixing depends on the distance scale at which the neutral weak force is viewed. The presence of weak mixing has observable consequences that have been extensively studied in high-energy experiments at CERN and SLAC. However, the dependence of this mixing on the distance scale has only recently begun to be mapped out by experiments carried out at lower energies. In particular, precise measurements of transitions in cesium atoms and neutrino-nucleus scattering provide conflicting information on weak mixing. While the atomic experiments now appear to agree with the standard model prediction, the neutrino-nucleus scattering experiment carried out at FNAL disagrees. The interpretation of the two kinds of measurements has been subject to controversy because of the complexity of the cesium atom and the target iron nucleus.

Recently, a new measurement of weak mixing using electron-electron scattering has been carried out at SLAC. Given the simplicity of the electron, the interpretation of the measurement is unambiguous and the result neatly agrees with the standard model prediction. The experiment separates the effects of the electromagnetic and weak interactions between electrons by observing an asymmetry in the rate of scattering that can result only from the weak force. A future program of weak mixing studies is now underway at JLab. The Qweak experiment will soon study weak mixing in elastic electron-proton scattering, while the 12-GeV Upgrade will facilitate additional sensitive measurements involving inelastic electron-deuteron and elastic electron-electron scattering. These measurements will not only yield a more detailed map of how weak mixing depends on distance, but will also provide a powerful "diagnostic tool" for probing new, neutral weak forces at short distances. Indeed, recent theoretical work has shown how detailed comparisons of these different electron scattering measurements with the standard model predictions may help distinguish between different possibilities for such forces, such as those generated by SUSY or additional, neutral weak force carriers.

F. Nuclear Theory

Major contributions from nuclear theory pervade all of the programs described above and are often specifically acknowledged. Thus detailing the many critical theory contributions to nuclear science since the last LRP would be redundant. Instead we provide a brief overview of the recent NSAC subcommittee report on nuclear theory, followed by a short description of opportunities in nuclear theory from enhanced computational resources that are now becoming available.

The 2003 NSAC Theory Report

One of first recommendations of the 2002 LRP stipulated:

> "Significantly increase funding for nuclear theory, which is essential for developing the full potential of the scientific program."

NSAC convened a subcommittee in 2003 to develop a response to the following charge from the agencies:

> "NSAC is asked to review and evaluate current NSF and DOE supported efforts in nuclear theory and identify strategic plans to ensure a strong U.S. nuclear theory program under various funding scenarios (constant effort and increased effort up to 50% based on FY03 level)."

The report produced by the subcommittee, "A Vision for Nuclear Theory," was transmitted to the agencies in October 2003. The report contains a broad assessment of recent achievements in nuclear theory as well as a list of scientific opportunities for the next decade. The report also contains a survey of funding and personnel issues affecting the research in nuclear theory in the U. S. Most importantly, the report makes a number of recommendations aimed at improving the effectiveness of theoretical nuclear physics research in support of the broader mission of the diverse nuclear physics programs supported by the agencies. Among these recommendations are:

- Competitive national fellowship programs for graduate students and postdocs.
- Enhanced OJI awards to outstanding junior theorists.
- Increased support for large-scale computing in selected fields.
- Topical research centers.
- Centers of excellence having multidisciplinary thrusts.
- Reduction or elimination of the disparity between DOE and NSF in support per principal investigator.

As a first response to these recommendations, the nuclear physics office in the Office of Science has allocated increased funds for computer hardware for QCD lattice computations as a joint initiative with the high-energy physics office. This initiative has permitted the purchase of about 10 Tflops of special purpose computers at Brookhaven National Laboratory, which has catapulted the U.S. lattice gauge theory community into an international leadership position. As described below, the investment will greatly benefit the nuclear physics program by making very much improved *ab initio* calculations of hadronic structure properties and the equation of state of nuclear matter possible. The agencies have indicated that they are considering a positive response to several other core recommendations, as well, if adequate funds can be identified in the out-year budgets. One unsolicited proposal for a topical research center has been formally submitted to the DOE, and other proposals are being prepared by members of the nuclear theory community.

A quick survey of nuclear theory personnel at universities and national laboratories indicates that the workforce is essentially flat at the former, while a modest growth has occurred in the number of supported personnel at national laboratories that, however, is not reflected in a proportional increase of the funding levels of these theory groups.

The research activity in nuclear theory since the 2002 LRP has continued at a very high pace, yielding significant progress in all areas of nuclear physics research, often with decisive impact on the experimental programs. Since most of these activities are closely linked to the overall progress of research in the various subfields, we do not list these recent achievements here, but refer to the other sections of this report. Below, we give a brief overview of the progress and challenges in core areas of nuclear physics, where scientific discovery through advanced computing has a significant impact, and theoretical research faces the greatest opportunities during the decade ahead.

Scientific opportunities in nuclear theory

Some key nuclear theory problems can be solved only through numerical simulations on multi-teraflop-scale computational facilities. The three areas in which this approach is central to scientific progress are:

- Understanding the confinement of quarks, the structure and spectrum of hadrons, and the phases and properties of hot QCD matter by means of lattice QCD calculations.
- Understanding the mechanism by which supernovae explode and elucidating the origin of the elements in these explosions by fully three-dimensional simulations of core collapse supernovae.
- Solving the quantum many-body problem for nuclei by exact quantum Monte-Carlo calculations.

Advances in computational physics and computer technology represent great opportunities for breakthroughs on these problems. And progress on these questions is crucial to realizing the full physics potential of the investments that have been made in CEBAF and RHIC and new investments that were recommended in the 2002 LRP: the rare isotope accelerator (RIA) and the deep-underground neutrino physics laboratory (a part of DUSEL).

The unique opportunity of the moment for focused investments in computational nuclear science arises because of the confluence of rapid progress in computational algorithms and great improvements in computer hardware. These advances over the past five years by the U.S. agencies and their foreign partners are the result of sustained investments in additional personnel and hardware development. For example, the new “QCD-on-a-chip” technology developed as a joint initiative of BNL, RIKEN, U.S. universities, and industrial partners has made it possible to build computers with about 10 times the performance of the previous generation at a cost of $1M per Tflop. The first two machines of this type, having 10 Tflop capability, have just begun their operation at BNL. These machines will allow U.S. scientists to generate the first rigorous solutions of QCD having realistic quark masses and the correct symmetries, in order to understand the physical mechanisms of quark confinement, to compute the quark-gluon structure of the proton, and to map out the phase diagrams of strongly interacting matter.

These advances are achieved by the use of optimized computer architectures for lattice QCD, which are approximately 30 times more cost-effective than the previous generation. Industrial spin-offs of the new technology are now enabling the installation of even more powerful computers for research and development in government laboratories. Recent advances in other areas of nuclear physics, especially supernova simulations and nuclear structure calculations, are dependent on the support of multidisciplinary networks of scientists who develop novel computational approaches to these problems.

Rigorous calculations of the structure of complex nuclei are at the verge of becoming feasible. For a growing range of light nuclei, exact solutions of the quantum mechanical equations can be obtained, starting from a microscopic interaction between the nuclear constituents. For heavier nuclei, approaches based on controlled approximations are being developed. Theorists, for the first time, will be able to connect the structure of these nuclei and the bulk nuclear matter to light systems and interactions rooted in QCD, making it possible not only to predict the stability of increasingly large nuclei, but also to determine with unprecedented precision the form of the interaction binding protons and neutrons together.

Advances in several areas of physics and in computer technology will combine to finally facilitate realistic three-dimensional calculations of the violent collapse and explosions (supernovae) marking the deaths of moderately massive stars. Such calculations are urgently needed to correctly describe the explosions observed by astronomers and to make precise predictions for neutrino signals in future underground detectors. The success of this ambitious and multidisciplinary program requires parallel developments in the theory of neutrino, energy, and matter transport, as well as improved models of nuclear reactions and decay processes.

Progress in other areas of nuclear theory is less dependent on investments in advanced computational facilities than on an increased workforce. This consideration is particularly applicable to theoretical opportunities in the study of neutrinos and fundamental symmetries, where the demand for theoretical input and guidance from the experimental community and the needs for interdisciplinary research overwhelm the present manpower resources. The recent breakthroughs in neutrino physics have opened up an exciting area of model building and phenomenology in nuclear theory. Future challenges include sharpening the implications of electric dipole moment searches and neutrino studies for the origin of baryonic matter, delineating the role of neutrino scattering and oscillations in shaping astrophysical processes, and refining nuclear structure calculations needed for the interpretation of precision tests of physics beyond the standard model.

The realization of these and many other scientific opportunities will require sustained investments in nuclear theory personnel and computer hardware at a substantially increased level. Those investments are minute when compared with the past and future proposed investments into experimental facilities, but the projected payoff in terms of the success of the overall physics program is immense.

G. Facilities

U.S. nuclear scientists utilize a broad range of facilities to carry out the program discussed in this report. They range from small university laboratories to the two major facilities, CEBAF and RHIC. In reviewing the DOE program, the subcommittee focused on the present and future science in QCD, nuclear structure and astrophysics, and the standard model and its possible extensions. We *did not* look in detail at the individual DOE and NSF low-energy facilities that carry out the program in nuclear structure and astrophysics and are aptly described in the last LRP. We *did* look in detail at both the programs and facilities at CEBAF and RHIC. Below we provide brief updates on the status of these two major facilities.

CEBAF at Jefferson Laboratory

CEBAF is a superconducting, continuous-wave accelerator with a maximum energy of 5.7 GeV and a 100% duty factor. It was commissioned just after the 1996 LRP was developed and has been a resounding success, matching or exceeding all design specifications. The racetrack-shaped accelerator, shown in **Fig. II-8**, consists of two parallel superconducting linac sections, joined at each end by nine isochronous magnetic arcs, which allow the beam to be recirculated up to five times. A radio-frequency separator allows extraction of beams having different energies to three experimental areas. Three distinct beams having currents differing up to a millionfold and a combined current of 200 µA can be injected simultaneously into the accelerator for delivery to the three experimental halls. CEBAF's capabilities are unique in the world. The combination of energies from about 0.8 to 5.7 GeV, a beam emittance of less than 1 nm·rad, an energy spread of about one part in ten thousand, and simultaneous operation of three halls with currents from 100 pA to greater than 100 µA is unmatched anywhere. Equally important is the availability of beams having polarization in excess of 75% at currents exceeding 100 µA, with minimal helicity-correlated variations of beam parameters.

The 12-GeV Upgrade Project

The key features of CEBAF that make an upgrade to double its energy cost-effective are easily defined. By the summer of 1994, CEBAF was the world's largest superconducting radio-frequency (SRF) accelerator. The linacs each include 20 cryomodules and each cryomodule in turn contains 8 five-cell SRF accelerating cavities. On average, these cavities exceed their design specifications by 50% in two critical performance measures: accelerating gradient and quality factor. It is the success of this technology—where JLab is a world leader—that has opened up the possibility of a relatively simple and inexpensive upgrade of CEBAF's top energy. The latent accelerating power of the installed SRF cavities has already brought CEBAF close to 6 GeV, 50% above its design energy, and recent successes in SRF development have led to the production of two cryomodules that are more than a factor of 2 more powerful than the original design. A staged development program underway aims at producing a cryomodule that exceeds the original specification by a factor of 5, using higher-performance seven-cell cavities that still fit into the same space as the original five-cell cryomodules. The cryomodule developed as the first step in this program already performs a factor of 4 better than the original specifications.

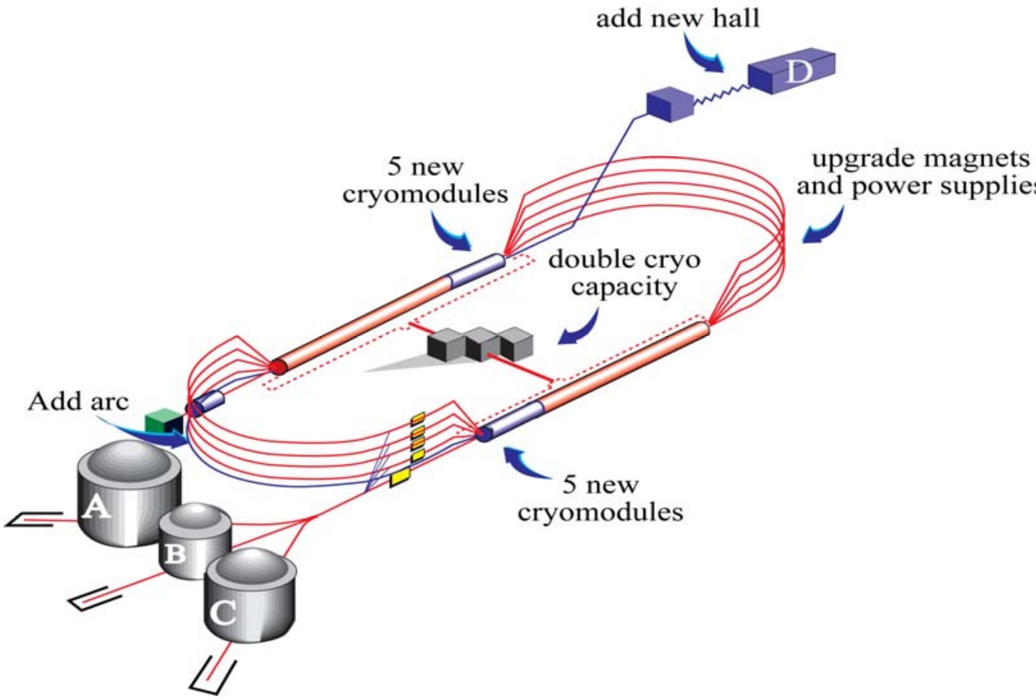

Figure II-8. Schematic showing the upgraded CEBAF at Jefferson Lab. The additions that are part of the upgrade are marked.

The Upgrade does not change the basic layout of the accelerator. There are four main changes: additional acceleration in the linacs, stronger magnets for the recirculation, an upgraded cryogenics plant, and the addition of a tenth recirculation arc. The extra arc permits an additional "half pass" through the accelerator to reach the required 12 GeV beam energy. The 12-GeV electron beam will be transported to a new Hall D, where it will be used to produce 9-GeV polarized photons to search for new exotic particles. The accelerator will also be able to simultaneously send electrons of 2.2, 4.4, 6.6, 8.8, or 11.0 GeV to the existing Halls A, B, and C.

The Experimental Equipment for the 12-GeV Upgrade

The equipment planned for the upgrade project makes good use of apparatus developed for the present program. In two of the existing halls (Hall B and Hall C), new spectrometers may be added and/or present equipment upgraded to meet the demands of the 12-GeV program.

In Hall A, the beam line will be upgraded to transport 11-GeV electrons. This hall will be used for large setup experiments and for experiments that require high resolution, high luminosity and the detection of reaction products with momenta between 0.4 and 4.3 GeV/c. There is already a backlog of more than five years for such experiments, and it is expected that this line of experimental research will continue well after the upgrade has been completed. Since only one of the present end stations will be able to take the 11-GeV beam at any given time, a lower-pass beam will always be available.

In Hall B, the CEBAF Large Acceptance Spectrometer (CLAS), which was designed to study multi-particle, exclusive reactions, will be upgraded to CLAS12 and optimized for studying exclusive reactions at high energy. It will also be used for selected valence quark structure studies involving neutron "tagging" or polarized targets, which support only very low beam current. Most importantly, the maximum luminosity will be increased by a factor of 10. The present time-of-flight counters, Cerenkov detectors, and shower counter will be retained, but the tracking system and other components of the central region of the detector will be changed to match the new physics goals. Major new components include superconducting torus coils that cover only the forward angle range, a new gas Cerenkov counter for pion identification, additions to the electromagnetic calorimeters, and the central detector.

In Hall C, a new high-momentum spectrometer (the SHMS, Super-High-Momentum Spectrometer) will be constructed to support high-luminosity experiments detecting reaction products with momenta up to the full 11-GeV beam energy. With the SHMS and its companion, the existing High Momentum Spectrometer (HMS), Hall C will be the only facility in the world capable of studying (deep) exclusive reactions up to the highest momentum transfers with appropriately high luminosity. The spectrometer will be usable even at very small scattering angles.

The GlueX experiment will be housed in the new above-ground experimental Hall D. A collimated beam of linearly polarized photons will be produced via coherent bremsstrahlung with 12-GeV electrons. The scattered electrons from the bremsstrahlung will be tagged with sufficient precision to determine the photon energy to within 0.1%. The primary element of the GlueX detector is an existing 2.25 T superconducting solenoid that is currently being refurbished. An existing 3000-element lead-glass electromagnetic calorimeter will be reconfigured to match the downstream aperture of the solenoid. The full detector includes a Cerenkov counter, a scintillator time-of-flight (TOF) wall, and a lead-glass calorimeter for detecting photons. The detector has complete particle detection coverage and has been optimized to search for exotic particles in the mass range from 1.5 to 2.5 GeV/c^2.

Upgrades for the far future: CEBAF II and ELIC

CEBAF options for the future include another upgrade to the present accelerator and an electron-ion collider. It is also possible to consider a future CEBAF upgrade to 25 GeV. This would fit within the current footprint of the accelerator, but would require substantial upgrades to both the acceleration cavities and the recirculation arcs. The present concept for a future electron-ion collider at JLab would be to build a new collider ring with an ion source at JLab. Electrons from the current CEBAF facility would be injected into the ring allowing electron-ion collisions.

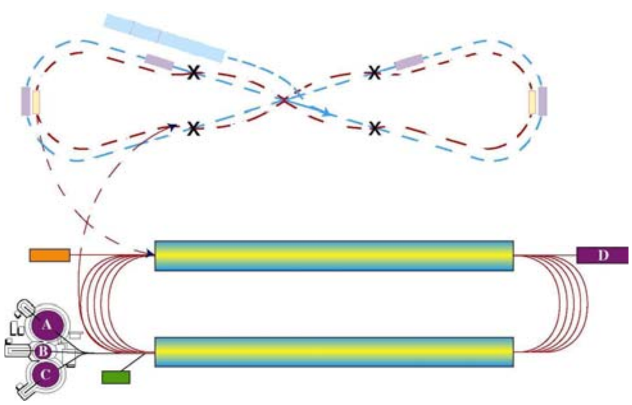

Figure II-9. Schematic drawing of the CEBAF accelerator feeding electrons into a possible future light-ion accelerator to provide for electron-ion collisions.

Technical Advances and Future Plans for the RHIC Facility

At the time of preparation of the 2002 LRP, RHIC had just begun operation. Its first measurements with beams of heavy ions had already produced groundbreaking results, providing the first hints of nearly perfect liquid flow of the hot, dense matter created in collisions of gold nuclei. But heavy ion beam intensities were low, and the accelerator and detectors were still in a commissioning phase. In the intervening years, the technical development of the facility has been rapid and impressive. The collision rates and fraction of time when the beam is available for physics have improved dramatically, culminating in 2004 and 2005 runs that produced vast quantities of heavy-ion collision data, with beam performances exceeding the most optimistic predictions. As the beam intensities have risen, so have the data-taking rate capabilities of the experiments. The two major detectors have added essential upgrades: extensive electromagnetic calorimetry to enable STAR to detect and trigger on high-energy electrons and photons; a second muon detector arm for PHENIX.

The scientific reach of RHIC has been greatly expanded by the parallel development, with exemplary international collaboration, of capabilities for high-energy spin-polarized proton beams. Essential new equipment added for this purpose to the accelerator complex over the past three years is highlighted in **Fig. II-10**. It includes specialized superconducting magnet systems (so-called "helical Siberian Snakes") needed to overcome the effects of hundreds of depolarizing resonances encountered during the beam acceleration process, and similar magnets to provide independent control over the beam spin orientation at the STAR and PHENIX detectors. The installation in 2005 of a similar "partial" helical Snake in the Alternating Gradient Synchrotron injector to RHIC should further improve the overall available polarization. In addition, newly developed polarimeters in RHIC monitor and calibrate the degree of beam polarization in this previously unexplored energy regime. Other state-of-the-art equipment includes an optically pumped polarized ion source and a polarized hydrogen gas jet target. A major fraction of the funding for all of this new accelerator equipment has been provided by the RIKEN Institute of Japan, which also supports related theoretical physics efforts at the RIKEN-BNL Research Center.

Considerable beam time was devoted during 2002-4 to commission this new equipment and to develop the luminosity and polarization necessary to meet the science goals of the RHIC spin program. Important progress was made in 2004 with the development of a new tune for the collider rings and a solution for vacuum breakdown problems previously encountered at high beam bunch intensities. There have also been significant detector upgrades motivated in part or in full by the needs of the spin program. STAR completed in 2004 an Endcap Electromagnetic Calorimeter, funded largely by NSF, to improve the determination of gluon polarization in a polarized proton. The second muon detector arm in PHENIX improves sensitivity to sea antiquark polarizations. Both collaborations have developed and installed critical local subsystems to monitor the beam spin direction at the detectors and the relative collision luminosity for different beam spin orientations. The facility, the detectors and both large collaborations (with fully integrated spin physics working groups) are now poised to exploit these innovative technical advances to extract a commensurate physics payoff in the first (200 GeV) phase of the spin program, beginning with a first long (~10 week) run in 2005. In addition preliminary tests of 400 GeV polarized proton operation have just begun.

Upgrades for the near future: Detectors and the Collider

A multi-pronged strategy has been devised for near-term upgrades needed to answer the fundamental open questions that have emerged from the RHIC discoveries to date for hot, dense matter. Just as large telescopes can be improved through installation of new optics, or by measuring at new wavelengths, the large detectors at RHIC can upgrade their “vision” with new subsystems that augment their existing capabilities. These improvements include precision vertex detectors to make critical measurements of charm and bottom quark production; extended particle identification to understand how each “flavor” of quark is transported in the medium; hadron-blind detectors to focus exclusively on the electrons sensitive to symmetry restoration and thermal radiation; and extensions in detector coverage to better reach the regions where color glass condensate effects are expected to be large. Other enhancements are contemplated for the maximum-energy (500-GeV) stage of the spin program to improve triggering capabilities and forward tracking resolution relevant to detection of intermediate vector bosons. These upgrades have been optimized to address, in the most efficient way possible, the entire array of issues listed in the RHIC science section of this report, while leveraging the $100 M (each) investments in the existing PHENIX and STAR detectors.

A corresponding series of accelerator upgrades is envisioned. An Electron Beam Ion Source (EBIS) will greatly extend the range of ion species that may be accelerated by the RHIC complex, offering the exciting possibility of uranium-uranium collisions, where the deformation of the nuclei can lead to much higher energy densities in some events. EBIS would also provide a capability for spin-polarized beams of ^{3}He ions, giving unique opportunities to study the spin structure of the neutron at an eventual eRHIC facility. EBIS would allow more economical and stable operation than the Tandem Van de Graaff that currently serves as the initial accelerator in the RHIC heavy-ion beam pathway.

Dramatic increases in heavy-ion collision luminosity are also planned. RHIC notably achieved stable operation at twice its design luminosity in only its fourth year of operation. But the rare probes required for various intriguing signals from the new state of matter demand still greater experimental sensitivity. A further factor of two increase in collision rate is anticipated by doubling the number of beam bunches stored in each collider ring. An additional factor of ten can be gained by adding electron cooling to increase the lifetime of the stored ion beams. An active R&D program is underway to develop the required accelerator components and demonstrate the accuracy of the simulation codes needed for this critically important collider upgrade at a construction cost of about $55M. The addition of electron cooling is also the first step toward implementing eRHIC and its precision QCD studies in gluon-dominated matter.

Upgrades for the Far Future: eRHIC

While several plans for an eventual electron-ion collider are under consideration, the scenario currently favored at RHIC involves the addition of a storage ring for spin-polarized electron and positron beams at energies between 5 and 10 GeV. As shown in **Fig. II-10**, this ring would intersect one of the existing RHIC rings at one interaction region, not presently occupied by a major detector. This layout would permit a new phase of the nucleus-nucleus collision program using the existing detectors at other interaction regions, while a major new detector would have to be added to study the electron-proton and electron-nucleus collisions that eRHIC enables. The electron beam would originate in a polarized source and be accelerated to full energy via multiple passes through a single linear accelerator having special arcs to permit beam recirculation. This injector would also include a conversion system to produce positrons. Attainment of collision luminosities suited to the science goals relies on the electron cooling upgrade for RHIC-II and on tripling the number of bunches that can be stored in the present RHIC ion rings.

The versatility of the RHIC accelerator complex and of its major collider detectors thus promises capabilities to maintain a forefront research program studying frontiers of QCD for many years to come. The various contemplated additions are highlighted in **Fig. II-10**.

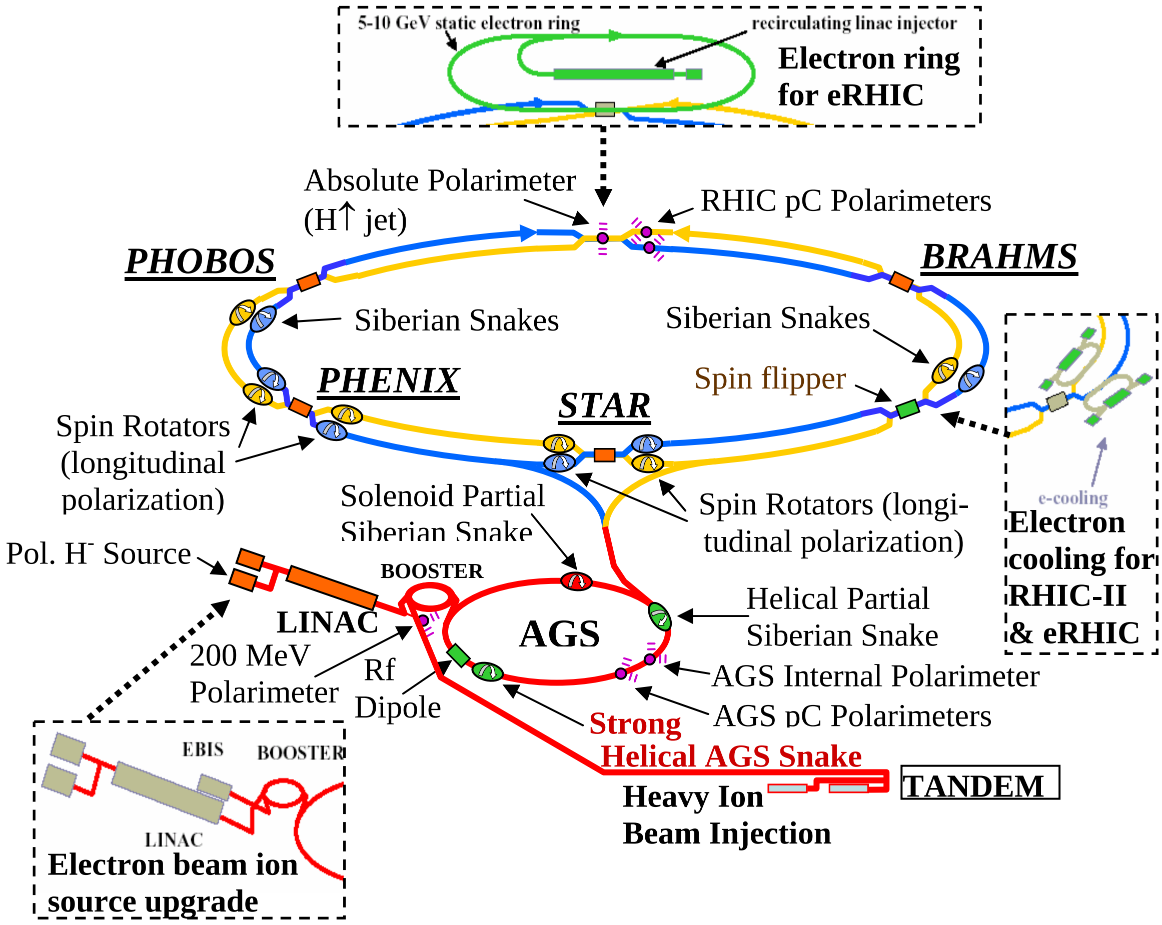

Figure II-10. Schematic layout of the present and possible future RHIC facility. Additions to the accelerator complex for the RHIC spin program and for various upgrade projects mentioned in the text are highlighted.

III. International Programs and Facilities

A. Introduction

The DOE operates two major, international facilities for nuclear science research at JLAB and BNL. Both CEBAF at JLAB and RHIC at BNL are relatively new, state-of-the-art machines, which draw researchers and major investments from the around the world. The U.S. also has three national user facilities that serve the broader international community. Two of these—ATLAS at Argonne National Laboratory and HRIBF at Oak Ridge National Laboratory—are operated by the DOE and the third—the NSCL at Michigan State University—is operated by the NSF. Other University and Laboratory-based programs that operate accelerators include five DOE labs—Texas A&M University, Triangle Universities Nuclear Laboratory, Lawrence Berkeley National Laboratory, University of Washington, and Yale University—and three NSF labs—Florida State University, Notre Dame University, and SUNY-Stony Brook. Nuclear scientists take advantage of special opportunities at facilities operated by high-energy physics (FNAL, SLAC), the DOE Basic Energy Sciences directorate (LANL-LANSCE, ORNL-SNS), and the National Institute of Standards and Technology (reactor).

CEBAF and RHIC provide powerful probes for studying QCD, the accepted theory of the strong interaction. Their complementary approach to providing data for testing this complex theory has yielded a number of new insights into the role of quarks and gluons in nucleons—the proton and neutron—and in nuclei. No other facilities in the world, either existing, under construction, or planned for construction, offer the breadth of coverage to study QCD that is afforded at these US machines.

Studies of nuclear structure and astrophysics are carried out at the ATLAS and HRIBF accelerators and the newly upgraded NSCL cyclotron complex. Together with university machines, these facilities are currently at the forefront to decipher the structure of nuclei and to discover the processes important to understanding the origin of elements in the universe.

The recent development of exotic rare-isotope beam (RIB) facilities worldwide is opening up exciting possibilities to extend the suite of available nuclei that can be studied. Already new phenomena have been found that have caused us to rethink our traditional view of nuclear interactions. Furthermore, the actual nuclear reactions posited to be responsible for heavy-element nuclear synthesis are beginning to be tested in the laboratory. Even with the upgraded facilities at the NSCL, the U.S. RIB competitiveness will soon fall behind when facilities now under construction in Japan and Germany are completed.

The nuclear physics-driven tests of the standard model, including measurements of fundamental parameters and symmetries, are carried out at a wide variety of special facilities here and abroad; in general, they do not involve a single dedicated accelerator. The programs include the use of cold and ultra-cold neutrons, neutrinos from high-energy accelerators or from the Sun, tests of ultra-rare nuclear decays in background-free, deep-underground mines, and special precision measurements of muon, pion, and kaon decays. The NSF is presently reviewing options to develop a deep-underground science and engineering laboratory (DUSEL). The DUSEL is an interdisciplinary facility and is expected to host priority nuclear physics experiments such as neutrinoless double beta decay and low-background, nuclear astrophysics reaction studies.

On-going and future research efforts supported by DOE and NSF extend to international facilities. In the following pages, we provide brief snapshots of most of the important world facilities that carry out nuclear physics research. Technical specifications of these facilities are mentioned only when it is valuable for a comparison of potential.

B. "Major" Dedicated International Facilities: Present and Planned

A "major" dedicated facility hosts numerous experiments simultaneously, has a broad international user community, and defines its primary mission as nuclear physics research. The particle accelerators at these laboratories have unique capabilities. CEBAF at JLab and RHIC at BNL satisfy this definition; there are no similar facilities operating outside U.S. borders at this time. However, two are under construction: the Facility for Antiproton and Ion Research at GSI (GSI/FAIR) in Germany and the Japan Proton Accelerator Research Complex (J-PARC).

GSI/FAIR: Facility for Antiproton and Ion Research
The GSI Laboratory in Darmstadt, Germany has been the site of a world-class heavy-ion physics program devoted to the study of compressed nuclear matter and nuclear structure. The laboratory is known for the discovery of some of the heaviest elements in the periodic chart. GSI is presently investing in a significant upgrade of their accelerator facilities in a complex of cooler-storage rings known as FAIR **(Figure III-1).** It will have substantial programs in the study of QCD using anti-protons; the study of dense, heated nuclear matter using relativistic heavy ions, tests of quantum electrodynamics using highly stripped atoms; study of the characteristics of dense, hot plasmas driven by heavy-ion beams; research using beams of rare isotopes.

The FAIR facility will produce beams of cooled antiprotons, giving new life to a physics program pioneered at the CERN Low-Energy Anti-proton Facility, which was closed in the mid 1990s, and the FNAL antiproton accumulator, which hosted a high-precision study of charm mesons. The focus of the FAIR antiproton-based physics program is the production of ordinary and exotic hadrons containing charm quarks. It is complementary to the GlueX program designed for JLab 12-GeV Upgrade, which is slated to study exotic hadrons with the light up, down and strange quarks.

The new facility also will produce fast beams of rare isotopes by a technique known as in-flight separation, where nuclear fragments are collected and focused to a beam using a large fragment recoil separator. The secondary beams at GSI will be produced by fragmentation of heavy projectiles, up to uranium, accelerated to energies of up to 2 GeV/nucleon and collected in the Super-FRS. The separated, fast, rare isotopes can be studied directly following the Super-FRS or captured in storage rings to react with internal targets or collide with electron beams. This latter capability will make the FAIR facility unique in the world.

The RIB capabilities of the GSI/FAIR project have been compared with those of RIA by an NSAC subcommittee in 2004, which was chaired by Peter Bond. The subcommittee concluded:

"RIA and the GSI future facility were designed for quite different purposes and each has unique capabilities." Moreover they stated, "While both facilities will produce rare isotopes by fast beam fragmentation and there is collaboration between the U.S. and European communities on R&D issues, we find that this overlap in capabilities is less than it would appear. It is clear that the RIA rare isotope research capability is more extensive than GSI. The question of whether an upgrade of GSI would duplicate the rare isotope capability at RIA is answered firmly in the negative." RIA has re-accelerated beam capability that GSI does not. In the area of overlap, RIA has a factor of 10 to 100 higher rare isotope beam intensities and hence will work at a different scale of discovery potential.

In addition to the rare isotope beams, FAIR will have a program using heavy-ion beams having beam energies of up to 45 GeV/u. Plans are underway to use these beams to explore a part of the nuclear phase diagram complementary to that of RHIC. GSI will study compressed nuclear matter having high baryon density (perhaps similar to that at the core of neutron stars), while RHIC studies hot dense matter having low baryon density (similar to the early universe).

The FAIR construction follows a three-stage approach, with completion of the full facility presently slated for 2015. At each stage, a portion of the ambitious physics program is enabled, beginning by 2011 with the upgrade of radioactive beams with SIS 18 and SuperFRS for RIB nuclear structure and astrophysics studies, then in 2013 first studies with protons and antiprotons and the final RIB intensity, and in 2015 a relativistic heavy-ion program

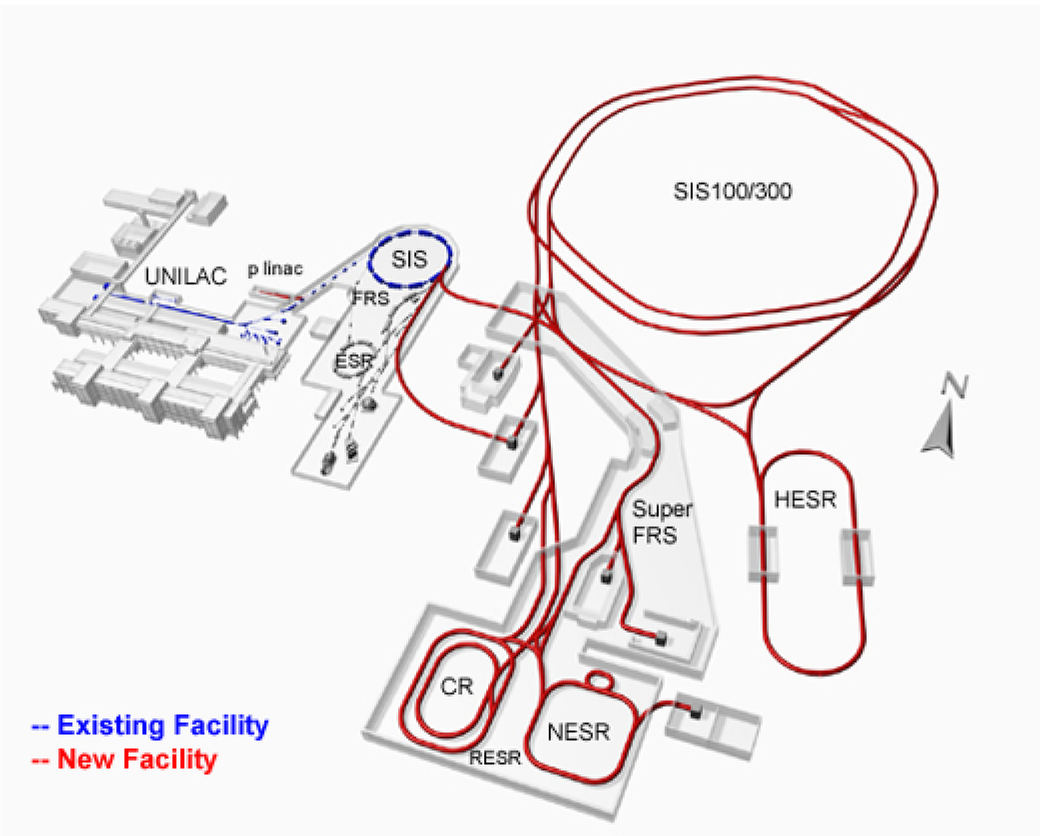

Figure III-1. GSI/FAIR facility, both existing and planned.

J-PARC: Japan Proton Accelerator Research Complex
Construction is well underway for the J-PARC facility shown schematically in **Fig. III-2**, which is anchored by a new, world-class 50-GeV proton synchrotron and a 3-GeV intense proton booster ring. Pion, kaon and antiproton beams—derived from the debris emitted in proton-nuclear target collisions—are planned, and a special energetic neutrino beam will be aimed toward the Super-Kamiokande underground neutrino detector, ≈300 km away, for the study of neutrino oscillations. The themes of the research program in high-energy and nuclear physics will include the study of hypernuclear states (nuclei having an implanted strange quark), dense nuclear matter, searches for new exotic particles, and high-energy proton scattering. The particle beams to be used in this research have been largely unavailable since the termination of the BNL AGS program. The J-PARC facility will be constructed in stages, beginning with the neutrino beam and a small number of secondary kaon beam lines.

J-PARC is a major three-community facility, providing particle beams for nuclear physics QCD research and neutrino, muon, and kaon beams for tests of fundamental symmetries and neutrino oscillation studies. Japanese nuclear physicists are world experts in hypernuclear physics. They carried out a limited, but very effective program at the AGS before the AGS program was terminated. In recent years they have worked at JLab, bringing their sophisticated detectors to bear on a wide variety of physics problems involving strange quarks. This area of physics has had limited participation by U.S. physicists and does not substitute for the on-going and future physics program in this area associated with CEBAF.

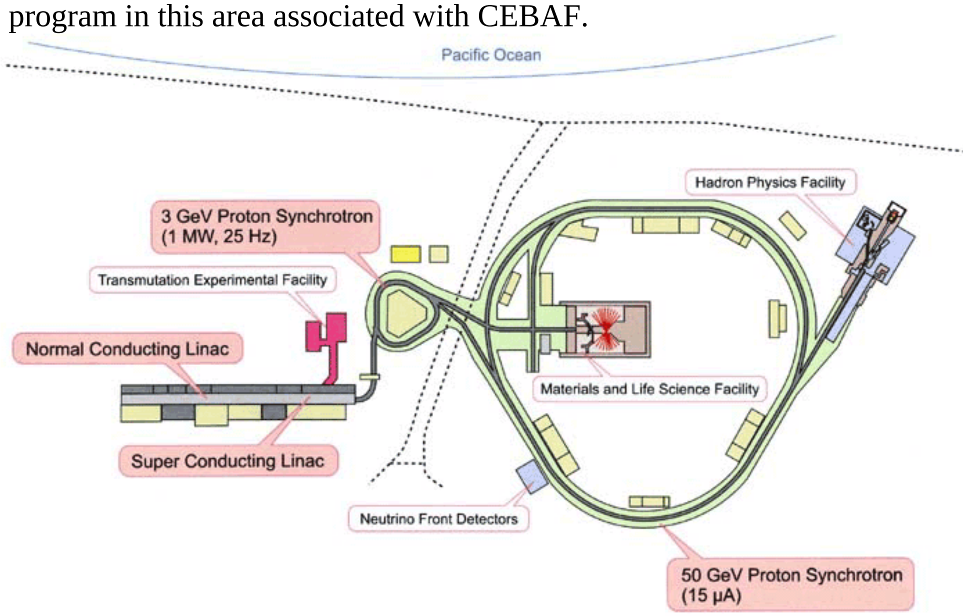

Figure III-2. J-PARC Facility Layout.

C. Major High-Energy Facilities having Planned or Existing Nuclear Programs

High-energy physics laboratories are large, multi-user facilities having accelerators designed to meet the needs and scientific priorities of their particle physics communities. Selected opportunities exist for nuclear physics programs, often involving a joint collaboration of nuclear and particle physicists, especially in the areas where the two subfields overlap.

CERN

This unique international facility includes a complex of accelerators and storage rings and a stand-alone RIB facility. Although CERN's highest priority is completion of the Large Hadron Collider (LHC) for particle physics, many opportunities for nuclear physics research are also supported at the laboratory. They include:

Spin physics at the CERN SppS

The CERN SppS —the proton-antiproton collider that led to the discovery of the *W* and *Z* bosons—is now used to create high-energy particle beams for fixed-target experiments in the north area of the extended CERN site. The COMPASS spectrometer is designed to enable a broad range of measurements in hadron spectroscopy and hadron structure, utilizing both hadron and muon beams. With the muon beams striking a fixed, solid polarized target, COMPASS will probe spin-orientation of gluons in a target of polarized protons. These measurements are complementary to those being carried out at the RHIC spin program, but they will not be nearly as comprehensive. The COMPASS program is expected to measure the gluon spin contribution to the proton at a single momentum fraction. The RHIC measurements will determine the gluon polarization to similar precision for a number of bins in momentum fraction, and thus will provide far better constraints on the total gluon contribution to the proton spin.

Relativistic Heavy Ion Physics at the CERN LHC

The LHC is slated to turn on by 2008. It will be the highest energy collider in the world, expanding the energy frontier by almost a factor of 9 compared to FNAL's Tevatron. The main goals of the two major detector collaborations, CMS and ATLAS, are to discover the Higgs and to search for new physics beyond the standard model. A particular focus is on the direct producton of supersymmetric (SUSY) particles, which could be responsible for the dark matter. SUSY particles—if they exist—would also affect, in predictable ways, many of the precision fundamental symmetry measurements being carried out by nuclear physicists.

Complementing the main LHC program is the accelerator's capability to collide heavy ions at energies approximately 30 times higher than RHIC. A special purpose detector, ALICE, is being constructed for relativistic heavy ion physics, and both CMS and ATLAS are sufficiently general in their detection capabilities to contribute to the heavy-ion program with only minor additions to their core designs. U.S. participation in all three experiments includes approximately 100 researchers at this early stage.

The LHC plans to run eight months of proton-proton collisions and one month of lead-lead collisions per year. The LHC heavy-ion program is complementary to that at RHIC. At RHIC, the hot, thermalized matter produced in the collision's wake is clearly distinguished from the effects of the huge number of interactions caused by gluons at low momentum fraction in the cold initial nucleus. At the LHC, this distinction should vanish, so that the combined influences of the predicted quark-gluon plasma (hot) and color glass condensate (cold) states will have to be unraveled to interpret measured particle spectra. The proton-nucleus or deuteron-nucleus experiments that might prove crucial to this unraveling require operation of the collider in an asymmetric mode, which has been discussed at LHC but which would require machine modifications. As the mechanisms for the unexpectedly rapid thermalization and nearly perfect liquid flow of the matter produced in RHIC collisions are only partially understood, it remains to be seen if similar conditions apply to the even hotter matter that should be produced at LHC. On the other hand, the much higher energies of the LHC promise substantially higher yields of such rare probes of the hot matter as very hard jets or bound states of heavy quark-antiquark pairs.

It is important to point out that the LHC will have no polarized proton capabilities and consequently no analog to the RHIC polarized proton-proton "spin" program. The acceleration of such polarized beams to LHC energies would be far more challenging than the significant technical barriers RHIC has already overcome to facilitate the spin program.

Rare isotope research at Proton-Synchrotron Booster (PSB)
The PSB is used to create rare isotopes at the ISOLDE facility using proton beam intensities of a few kW to produce rare isotopes in a hot target where the ions diffuse out and are ionized, the isotope separation on-line (ISOL) technique. The ISOLDE facility has performed rare isotope research for more than 30 years and has been one of the leading programs in this area. Within the past few years, CERN has added a re-accelerated beam capability for light ions, REX-ISOLDE, which has performed first experiments. Intensities at the facility are below those available at TRIUMF for many beams.

HERA in Germany
The HERA machine is an electron (or positron)-proton collider. The HERMES nuclear physics experiment has operated at HERA since 1995, using the 28-GeV electron ring to intercept an internal polarized or unpolarized gas target. The physics probed includes pioneering deep inelastic, spin-dependent scattering studies, and the HERMES collaboration has met its original goal of separating the flavor dependence of the spin carried by the quarks. They have also made a coarse measurement of the gluon contribution to the proton spin, $\Delta G/G$, at a single measurement point, have observed deeply virtual Compton scattering, and have established important results on the transverse (sideways polarized) nature of quarks in hadrons and hadron formation in cold nuclear material. Many initial studies by HERMES have paved the way to next-generation work at RHIC-spin, CERN-COMPASS and the future JLab 12-GeV Upgrade. The HERA, and consequently HERMES, program will terminate in 2007.

D. International "Intermediate-Scale" Facilities and Programs: Present and Planned

An "intermediate-scale" facility or program is similar in scope to the special-purpose U.S. facilities or to a modest nuclear physics program at a large multipurpose facility. These research efforts will often have many international collaborators, but most of the work generally involves a high participation from local physicists. Comparable U.S. facilities and programs would include MIT-Bates, the MSU-NSCL, ATLAS, HBRIF, and LANSCE.

MAMI (Mainz MIcrotron), Germany
The Mainz MAMI-B microtron presently provides an electron beam having a peak energy of 850 MeV. It can best be compared to the MIT-Bates accelerator, which is being decommissioned in 2005. Both machines have had an impressive and rich history of precision measurements using low-energy electromagnetic probes and polarized beams. The Mainz machine energy will be doubled with the completion of the MAMI-C harmonic double-sided microtron. The extended energy range will result in a solid physics program for the foreseeable future and will directly overlap with the low-energy range of CEBAF. Instrumentation will include the SLAC Crystal Ball, the GSI kaon spectrometer, and an upgraded calorimeter to continue the measurements of parity violation. A limited U.S. participation is expected to continue at this facility.

Electron accelerator ELSA at Bonn, Germany
The low-intensity electron accelerator at Bonn can deliver nanoamperes of extracted beams of polarized or unpolarized electrons with a variable energy up to 3.5 GeV. While the energy peak overlaps with that of CEBAF, the limited beam intensity (CEBAF can deliver up to 100 μA, almost 100,000 times higher), restricts the physics program to very selective opportunities. ELSA is not competitive with the CEBAF program.

COSY (light-ion storage ring), at Jülich, Germany
The cooler ring, COSY, at the National Research Centre, Jülich, Germany, provides proton and deuteron, polarized or unpolarized beams having very precise energy and spatial characteristics. These "surgical" hadron probes have been employed for experiments using internal targets and external targets, with a physics focus on the production of mesons and hyperons close to threshold. The future program will include symmetry tests, studies of symmetry breaking in hadronic reactions, and measurements of specific hadronic bound systems that will probe hadron structure and interactions. The present plans calls for the COSY program to continue until the GSI/FAIR project is launched.

Paul Scherrer Institut (PSI) at Villigen, Switzerland
The PSI cyclotron is a relatively low-energy proton accelerator having a high beam current. At nearly 2 MW, it is one of the highest beam-power accelerators in the world. The facility will continue to operate for the foreseeable future and the proton intensity will be increased by 50 percent following a series of machine upgrades Secondary pion and muon beam lines are devoted to condensed matter (μSR) studies and to selected nuclear and particle experiments. The proton beam also drives a spallation neutron facility, a port of which is envisioned to be used in a new neutron electric dipole moment (EDM) search (which is not competitive with the U.S. plan). The nuclear and particle physics experiments presently hosted by the facility include pion beta decay, muon capture on the proton, positive muon lifetime, and a sensitive search for lepton flavor violation in $\mu \rightarrow e\gamma$ decay. The first three of these experiments are led and largely dominated by U.S. university groups.

Tri - University Meson Facility (TRIUMF) at Vancouver, Canada

The TRIUMF cyclotron has an extensive nuclear and particle physics program, centered on rare isotope research and the TWIST muon decay Michel parameter determination. The TRIUMF proton beam intensity is roughly 15 times smaller than that at PSI, but the facility is able to use up to 50 kW of beam for rare isotope production. Thus, TRIUMF is able to produce the highest intensity reaccelerated rare isotope beams currently available anywhere in the world. ISAC-I produces beams at energies relevant for astrophysical studies. An upgrade that is expected to be completed in 2006 will provide a higher-energy reaccelerated beam for nuclear structure studies. The facility is limited to beams of lighter elements and those that can be produced by the ISOL technique. Nevertheless, it will be a world-leading facility for the foreseeable future.

Institut Max von Laue-Paul Langevin (ILL) in Grenoble, France
A 58-MW reactor is used for studies of neutron beta decay and for a series of experiments that have set the present world's most sensitive limit on the EDM of the neutron. Measurements planned for the Fundamental Neutron Physics Beamline at the SNS will overlap with the program at ILL. Experiments having similar physics goals are now being carried out at the LANSCE and NIST facilities. We can expect the program of fundamental physics measurements at ILL to continue and to be competitive with experiments in neutron beta decay and the neutron EDM. Due in part to the charges incurred by users at ILL, no U.S. groups are presently working at the facility.

RIKEN at Wako, Japan
The RIKEN laboratory operates a separated sector cyclotron that is able to produce high-intensity, medium-mass heavy-ion beams of up to 100 MeV/u for nuclear structure studies. The primary focus of the laboratory is the production of neutron-rich rare isotopes having intensities approaching that of the NSCL. The facility has recently started study of superheavy elements and has tentative evidence for the observation of element 113.

The RIKEN laboratory is in the middle of a major upgrade to increase its heavy-ion beam intensity by a factor of 100 and the energy by a factor of 4. The Radioactive Ion Beam Facility, RIBF, will be the world-leading facility for in-flight production of rare isotopes when it is completed in 2007. It has the potential to nearly reach the intensity of the GSI/FAIR facility.

GANIL in Caen, France
The GANIL facility is devoted primarily to nuclear structure studies. It features two large cyclotrons that produce heavy-ion beams of up to 100 MeV/u. These beams are used to produce in-flight separated rare isotopes of modest intensity. GANIL was the first medium-scale facility devoted to such studies. Consequently, many new isotopes and important first results were discovered using this facility, notably the observation of the exotic ^{48}Ni and ^{100}Sn nuclei.

GANIL has recently commissioned a re-accelerated ISOL beam facility, SPIRAL. It will use the heavy-ion beams from the large cyclotrons to produce isotopes in a graphite target. The rare isotopes are then extracted, ionized and re-accelerated up to 30 MeV/u. This facility now has an extensive program in the study of medium- and mid-mass rare isotopes.

The laboratory has proposed to make a further upgrade, SPIRAL II, which would use a high-power deuteron linac (100 kW) to produce neutrons that would fission uranium and produce large quantities of mid-mass rare isotopes. This facility could be operational around 2010 and, if built, would provide the highest intensities for re-accelerated beams for selected elements of any facility until RIA is constructed.

Other facilities:
A number of smaller scale facilities are operated around the world for the study of nuclear structure and nuclear astrophysics. The cyclotron lab at Louvain La-Neuve was the first re-accelerated rare isotope beam facility in the world and still has competitive beam intensities for some ions. The cyclotron lab at Jyväskylä in Finland operates a facility that is devoted to the study of nuclear structure. They are known for their innovative equipment developments that have enabled, among other things, the study of the structure of the heaviest elements. The nuclear physics laboratory at Dubna operates several cyclotrons that produce heavy-ion beams up to 20 MeV/u. The very high intensity of these machines is used for superheavy element research and a limited number of studies of very neutron-rich light isotopes.

IV. Nuclear Science Workforce

Nuclear science is a key component of the nation's research capabilities. In addition to providing fundamental insights into the origin, evolution and structure of matter, nuclear scientists create knowledge and devices directly applicable to the nation's security safeguards, energy resources, health needs, environmental protection, and economic vitality. Nuclear scientists constitute an essential component of the nation's technical workforce. The NSAC Subcommittee on Education recently completed (November 2004) a comprehensive study, "Education in Nuclear Science." The report presents a detailed, current picture of the demographics of nuclear science with the aim of understanding the "Ph.D. pipeline." Key findings of the subcommittee include the following:

- The average annual production rate at U.S. universities over the last decade is 84 Ph.D.'s in nuclear physics and 10 Ph.D.'s in nuclear chemistry.
- Nuclear physics Ph.D. production by U.S. universities has declined by 30 percent since 1995.
- About one-half of the nuclear science Ph.D.'s obtained in U.S. universities were awarded to foreign nationals.
- The current rate of Ph.D. production is insufficient to meet future demand. An estimated increase by 20 percent is needed to fill anticipated research positions in non-academic areas, such as national security and homeland defense, nuclear medicine, environmental monitoring, and nuclear energy.

Young people typically enter nuclear science by earning a Ph.D. in physics or chemistry, undertaking original research carried out under the supervision of a university faculty member. Often the research takes place at one of the forefront national research laboratories operated by the DOE and NSF. It is these exciting research opportunities, coupled with modern university infrastructure, that draw the best students to the field. Upon completion of the Ph.D., the young nuclear scientist can choose to launch a career in academia, at government laboratories or in private industry, where his/her expertise and training are highly sought. A survey of nuclear science faculty, carried out for this report, indicated that their master's and Ph.D. graduates took the following career paths:

- 20 percent were in basic research positions at national laboratories
- 20 percent were professors at universities or undergraduate institutions
- 28 percent were working in business/industry/NASA
- 13 percent were working on national defense/safeguards
- 8.8 percent were in nuclear medicine
- 3.8 percent were in education or outreach
- 3.9 percent were working on environmental issues
- 2.5 percent were working on nuclear power or other energy technology

These findings agree with those of the 2004 NSAC report and underscore the important contributions of nuclear science to the technical infrastructure of the U. S. Only about 40 percent of nuclear science Ph.D. recipients stay in basic research—at a national lab or in academia. The remainder fill positions related to national technology needs and represent an important transfer of expertise to the private sector.

The 2004 NSAC report broadly concluded that the workforce production was marginally sufficient to supply *current* nuclear activities in academia, both basic and applied research at the national labs, and private industry. However, it identified a number of factors that strongly suggest an increased demand for nuclear scientists in the coming years. These factors include increases in research and development for national security and homeland defense, increases in retirement rates at the national laboratories as that population ages, and increases in the need for nuclear engineering and nuclear medicine. The conclusion is that an *increase* of Ph.D.'s—20 percent greater than the current rate of production—will be required to meet the demand for nuclear scientists over the next 5 to 10 years.

Homeland Security

One important area of nuclear science experiencing rapid growth since the 2002 Long Range Plan is research and development for the Department of Homeland Security (DHS). Long-term, high-payoff R&D will be supported by DHS; the DHS Science and Technology Directorate (within the Defense Nuclear Detection Office [DNDO]) covers all aspects of R&D for homeland security and has an FY06 budget request of $1,368 M (http://www.dhs.gov/dhspublic/). At this level of funding, and given their nuclear-related needs, the DHS alone will require a major increase in its nuclear science workforce over the next 10 to 20 years.

While precise quantitative measures are hard to obtain, one national lab (Lawrence Livermore National Laboratory) has seen an increase demand of 8 FTEs per year (13 percent) for DHS activities in nuclear physics alone. At Los Alamos National Laboratory, no less than ten programs currently rely on or are a direct outgrowth of basic nuclear physics research. At this rate, the increased demand by the national laboratories alone would use all of the increased Ph.D. production recommended by the NSAC report. Idaho National Laboratory anticipates growth in three of its four areas of nuclear science activities: basic research, nuclear energy, and homeland security, which would add an additional 2–4 nuclear science Ph.D.'s per year to the demand.

Nuclear-science applications are particularly important to DHS. For example, nuclear reactions using different probe particles, typically at MeV energies, could be used in nondestructive assays for high-throughput cargo screening. To explore these possibilities, the DHS recently established the Domestic Nuclear Detection Office (DNDO) to "develop, acquire and support the deployment of a domestic nuclear detection system to detect and report any attempt to import or transport a nuclear explosion device, fissile material, or radiological material intended for illicit use." These detection systems are challenging applications of the very technologies developed in low-energy nuclear physics experiments. The goal is to combine high detection probability with low "false positive" detection rates. The signature of illicit materials and devices is the presence of specific isotopes. The characteristic radiations of these isotopes, gamma-rays and neutrons, provide a means of identifying suspect cargo. Some techniques also require a probe of neutrons or gamma-rays to "interrogate" the cargo; the answer to the interrogation is the subsequent radiations of the nuclei. These methods draw heavily on nuclear expertise in detector development, experimental simulation, source design, and analysis. University nuclear scientists, in collaboration with industrial partners, are already using their laboratories to develop prototype screeners. For example, prototype projects using both neutron- and photon-beam techniques are underway at MIT.

Radiochemical techniques are also important forensic tools in determining the characteristics of nuclear explosions. These techniques employ cross-section measurements for the processes that drive the nucleosynthesis of isotopes exposed to a high flux of neutrons. Obtaining this basic information, the cross sections, is an important contribution that the low-energy nuclear physics community makes to the homeland security program.

Stockpile Stewardship

Low-energy cross sections are also of importance to the nation's stockpile stewardship program. Recently, a new initiative was launched by the National Nuclear Security Agency (NNSA) to encourage collaborations on stewardship-related problems between university researchers and NNSA-supported research groups at the national labs. A goal of the program is to ensure an adequate workforce to meet U.S. security needs. A specific component of the new program involves developing new techniques to determine reaction rates that are important for the stewardship program. The expertise and advanced techniques developed by Ph.D. students to make neutron-capture cross-section measurements are directly relevant to NNSA interests.

Nuclear Energy

Nuclear power as a reliable source of energy for the future is increasingly an important priority for the nation because of declining domestic oil reserves, increasing dependence on foreign oil, and mounting concerns about greenhouse gases and global warming. Nuclear science faculty play an important role in educating and training nuclear engineers at universities and, as demonstrated by the workforce demographics, nuclear scientists are attracted to working directly on energy issues. The report from the DOE Energy Secretary's Nuclear Energy Task Force in January 2005 called on DOE to enhance its role in educating and training future scientists and engineers for careers in DOE-related technical areas. In particular, it stated: "One important aspect of these efforts is development of the manpower that is essential for the resurgence of nuclear technology." It is important to note that no nuclear plants have been ordered since 1978 and no units are currently under active construction. The Tennessee Valley Authority's Watts Bar 1 reactor, ordered in 1970 and licensed to operate in 1996, was the most recent U.S. nuclear unit to be completed. As a consequence, very few people have been trained recently in this area and the expected re-emergence of nuclear power will require a newly trained nuclear science workforce.

Nuclear Medicine

Nuclear medicine continues to be a growing field with close ties to nuclear science. Beams of ionizing radiation, magnetic resonance imaging, and the use of radionuclides are all increasingly used to diagnose and treat medical ailments. The U.S. Department of Labor expects the employment of nuclear medicine technologists to grow faster than the average for all occupations through the year 2012. Growth will principally arise from an aging population, the primary users of diagnostic procedures, including nuclear medicine tests. Although many of these positions do not required an advanced degree, the need for these specialists underscores the importance of nuclear science education at the undergraduate level in universities and colleges. Here nuclear chemists make very significant contributions by teaching nuclear and radiochemistry within the chemistry curriculum, commonly a degree path to many medical professions. Nuclear chemistry Ph.D.'s, with their undergraduate training in chemical techniques, provide an important resource for basic research programs in nuclear medicine, as well as in clinical applications. While nuclear chemists made up only 13 percent of those responding to the survey, they accounted for about a quarter of the graduates in nuclear medicine.

Radiation Hardness Testing

A growing application that involves the direct use of nuclear science facilities is testing the radiation hardness of electronic circuits. As components become smaller, they are more susceptible to disruption from the effects of ionizing radiation passing through the device—a major problem in satellite and communication applications and a growing problem in large computer arrays. The industries and government agencies working in this area have determined that electronic circuits should be tested at several different facilities, depending on the particular application. The facilities being used today for this work include those at Brookhaven National Laboratory, the Indiana University Cyclotron Facility, Lawrence Berkeley National Laboratory, the National Superconducting Cyclotron Laboratory at Michigan State University, Texas A&M University, and Yale University.

Training the Workforce

It is important to underscore that the workforce needs discussed here are met directly by the nuclear science field. Often the breadth and specificity of the knowledge required for advancement in applied fields is difficult to acquire outside of Ph.D. research. Students trained in other fields do not gain sufficiently detailed knowledge of nuclear properties and of the most advanced nuclear techniques. Moreover, it is Ph.D. study in nuclear science that provides advances on relevant problems, such as techniques for the detection of naturally occurring and induced radioactivity. For example, combining this knowledge with a background in chemistry gives the nuclear chemist important skills relevant to environmental transport of radioactive materials and the use of radioactive tracers.

A broad range of other, more general, skills acquired by students in nuclear science are not easily replaced by students in other physical science disciplines—troubleshooting complex engineering systems, mining data from large data sets, working in large collaborations on forefront instruments, modeling advanced theoretical concepts, differentiating large effects from small ones, exploiting advanced mathematical techniques, and developing large-scale computer simulations of complex systems. Consequently, graduates of nuclear science Ph.D. programs are always in demand, and unemployment has remained at the 1-percent level for decades.

To ensure an adequate Ph.D. pipeline to meet these national needs, the potential pool of nuclear scientists must be expanded to include individuals from groups not currently well represented in the nuclear science workforce. Either the constant-dollar or constant-effort FY06 scenario will likely exacerbate a recognized current weakness in the U.S. science program—the under-representation of women and minority groups. As the recent GAO report *Gender Issues: Women's Participation in the Sciences Has Increased, but Agencies Need to Do More to Ensure Compliance with Title IX* notes, the U.S. will need to attract men *and* women to remain competitive in both its fundamental and applied science efforts. The 2004 NSAC report states:

"We recommend that there be a concerted commitment by the nuclear science community to enhance the participation in nuclear science of women and people from traditionally underrepresented backgrounds and that the agencies help provide the support to facilitate this enhanced participation." One of the major tactics that can be expected to lead to an increase in the participation of women and minorities in science is the presence of female and minority role models. Unfortunately, many female and minority nuclear scientists currently hold relatively junior positions in the community, making them the most vulnerable to budget cuts. While the NSAC education report shows progress in the number of women junior faculty, every effort must be taken to protect this gain. For the recent increases in women in the field to have a lasting effect, stable career positions must be assured. Funding cuts in nuclear science will not only discourage the creation of new faculty positions, but will also imperil the retention in nuclear science of positions opened by retirements. Without adequate representation in faculty positions by all segments of our community, the diversity of future generations of nuclear scientists is at risk.

As outlined in this section, and highlighted in the 2004 NSAC Education report, the constant-dollar and constant-effort budgets do not allow the increases in Ph.D.'s required to meet the expected workforce needs in nuclear science. In the constant-effort FY06 or constant-dollar "flat-flat budget" 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 lead to an exodus of many of the young people from nuclear science and the ability to attract a new generation would be seriously undermined. Nuclear chemistry positions are particularly at risk, as recent large increases in federal funding for biochemistry and nanoscience have driven new hires into those fields at the expense of nuclear science. In the long term, the Ph.D. production level is expected to drop by at least 25 percent and overall production to meet societal demands will be roughly half of that required. Delays in constructing new facilities, such as RIA or DUSEL, will further discourage adequate Ph.D. production.

The nuclear science community clearly needs to expand its efforts in training the next generation of nuclear scientists. The demand for these highly talented individuals will very soon outstrip the supply. By pursuing research at the cutting edge of our science, we will continue attracting the best and brightest students to the field.

V. Charting a Course—Findings and Guidance

A. The Science Background

The 2002 LRP is the starting point for the considerations of this subcommittee. Since the plan was crafted, nuclear scientists have made many major advances. Recent highlights include:

- Results from the SNO and KamLAND detectors that require neutrinos to have a mass
- Discovery of a new form of matter at RHIC
- Precision measurements of the charge, current and strangeness content of the proton and neutron at CEBAF
- Measurements at HRIBF and NSCL of nuclei far from stability that have properties deviating sharply from predictions, which have forced major changes in our understanding of nuclear structure
- Laser-beam trapping of a rare isotope of helium at ATLAS that has provided the first direct measurement of a long-sought piece of the nuclear force
- New measurements at university labs of a stellar reaction rate that increases the lower limit on the age of globular clusters in the universe
- Development of dedicated tera-scale computer facilities to solve QCD on the lattice.

These advances have come as a result of careful planning and investments that, in some cases, span several decades. Standing behind the breadth of the headlines are scientific results of extraordinary depth. We have attempted to capture some of the excitement surrounding work completed since the last LRP in this report.

The present nuclear science program has been strongly influenced by events that occurred just over three decades ago. The observation at SLAC of clear evidence for substructure in the nucleon led to the birth of QCD—a theory that explained the substructure of the nucleon in terms of quarks and gluons. By the late 1970's, it was clear that a theory of the nucleon-nucleon interaction derived from first principles would require a better understanding of the fundamental strong interaction embodied in QCD. Without this, physicists would be forever relegated to using effective forces that were derived from fits to nuclear data. A multi-GeV electron accelerator was widely recognized as the ideal tool to study nuclear structure and this new theory. In 1979, this concept was transformed into a recommendation in the first LRP of nuclear science. Sixteen years later the first experiments were carried out with CEBAF at JLab.

As theorists investigated QCD, it became apparent that the new theory also held a missing key to the early evolution of the universe: a phase transition was predicted to occur between the primordial sea of elementary particles and the birth of nucleons in the very early epoch following the big bang. The state of matter existing prior to the phase transition was named the quark-gluon plasma (QGP). This astonishing hypothesis led quickly to a search for ways to replicate the QGP in the laboratory and to study the phase transition. Collisions of heavy ions accelerated to extremely high energy offered the best hope for achieving the high energy density needed to produce the QGP. This opportunity launched a whole new field, spearheaded by nuclear scientists. It also led, in 1983, to the recommendation in the second LRP to build RHIC. With the construction of CEBAF and then RHIC, nuclear scientists now have the necessary tools to probe QCD, a central focus of our field.

Both CEBAF and RHIC are world-class facilities. Nations from around the globe have made major investments in instrumentation and scientific manpower at these facilities. With the completion of the HERA program in Germany, CEBAF and RHIC are now the world's only machines dedicated to the study of QCD. But this capability comes at a price. The resolving power of these two "microscopes" must be high to probe the substructure of the nucleon. This requirement translates to high-energy accelerators and complex detectors that require substantial funds to operate. We must find a way to pay this price if we hope to understand the fundamental theory of the strong interaction.

While the study of QCD is an important component of nuclear science, it is only a part of our discipline. At the core of our science is the study of nuclei and nuclear reactions. Over the past five decades, we have amassed an enormous wealth of information about the structure of stable nuclei and those near stability. From these data, we have constructed models to explain the observed phenomena. But the models are far from complete; they often fail to predict nuclear properties for systems that are several nucleons removed from those used in the model database. For example, recent experiments demonstrating changes in nuclear shell closures far from stability highlight shortcomings in our understanding of stable nuclei. This interdependence between experiment and theory reinforces expectations that we must push measurements to the extreme limits of nuclear stability to make significant progress in nuclear structure theory.

Access to nuclei very far from stability is also crucial to delineate reaction rates and decays of nuclei that participate in explosive nucleosynthesis in stars. The rapid capture of protons (the rp process) and neutrons (the r process) in stellar explosions occurs at the edges of proton and neutron stability. In the last decade, we have obtained some crucial new information on rp-process nucleosynthesis. But very few of the nuclei that participate in the r process are accessible now, nor will they be—even at a new generation of exotic-beam facilities being developed outside the U.S.—until the Rare Isotope Accelerator (RIA) is built. If present funding trends persist and RIA is unduly delayed, or cancelled, the U.S. will be in jeopardy of losing the opportunity to discover and exploit new science in this core component of our field.

Determining neutrino properties and carrying out low-energy tests of fundamental symmetries are also essential components of the nuclear science portfolio. Nuclear scientists have played key roles in the recent discovery of neutrino oscillations, and we continue to set limits on physics beyond the standard model using precision symmetry tests. Through a new Major Instrumentation Equipment (MIE) grant from DOE, nuclear science has a commitment to carry out future symmetry tests at the Spallation Neutron Source with the Fundamental Neutron Physics Beam Line. We are also supporting ongoing R&D efforts for a new generation of detectors to probe the neutrino mass scale and to help complete the fundamentally important story of neutrino oscillations.

To avoid duplication of effort and to maximize science potential, the world-wide nuclear science community has developed a mechanism through the Organization for Economic Cooperation and Development's Global Science Forum (formerly the Megascience Forum) for planning large facilities. In this context, the U.S. has an acknowledged leadership role in QCD studies via high-energy electron scattering at CEBAF and high temperature and high density studies at RHIC. Facility planning outside the U.S. has focused on other areas. A major upgrade of facilities at GSI in Germany and a new laboratory, J-PARC in Japan are excellent examples of this coordinated effort. The GSI/FAIR facility will provide unique beams of antiprotons for targeted studies in fundamental symmetries and QCD. The facility will also produce a wide array of rare isotope beams. While not a substitute for the capabilities of RIA, it will be a major step forward in the world's ability to study nuclei far from stability. With the completion of J-PARC, the world will have a dedicated high-energy, high-intensity hadron facility that will provide a wide-ranging research program including accelerator-based neutrino oscillation studies, fundamental symmetry tests and targeted QCD studies through measurements of hypernuclei.

U.S. scientists have played and will continue to play major roles in international collaborations at our own facilities and those abroad. In neutrino physics, both the SNO and KamLAND detectors are housed outside the U.S. We expect international collaborations to form and to carry out the next-generation measurements in neutrino oscillations and double beta decay. We have already pointed out the strong international contributions to the programs at CEBAF and RHIC.

The NSAC subcommittee considered, in the international context, each of the components in the broad portfolio of DOE nuclear science to develop its conclusions about the future. We present the subcommittee findings below. The impact of various budget scenarios on our field is discussed in the subsequent section.

B. Subcommittee Findings

In 2002, NSAC laid out a framework for the coordinated advancement of our field. This LRP gave highest priority to the following efforts:

- Exploitation of the U.S. investment in three unique, world-leading facilities—RHIC, CEBAF and NSCL
- The construction of a world-leading rare isotope accelerator (RIA)
- The construction of a deep underground science laboratory (DUSEL, an NSF initiative)
- A cost-effective upgrade of the CEBAF accelerator at JLab (the 12-GeV Upgrade).

Since 2002, the justification for this program has become stronger and more focused thanks to major discoveries in neutrino physics, the extraordinary blossoming of the RHIC program and an even more compelling scientific justification for the 12-GeV Upgrade and the RIA. The recommendations of the 2002 Plan are still valid, and provide the best guidance for the optimal development of our field.

Unfortunately, these are difficult times. Pressures on the Federal Budget are forcing all branches of science to examine their portfolios to ensure that the U.S. has the most cost-effective program in an international context. After a review of the present nuclear physics program, undertaken with a deep sense of urgency, we provide the subcommittee's findings to guide the implementation of the 2002 Long Range Plan.

- **The recent discovery of a new form of matter at RHIC having temperatures characteristic of the earliest moments of the universe presents a dramatic science opportunity demanding further exploration. RHIC's unique capabilities will also allow it to resolve the role of gluons in the spin of the proton.**

The RHIC experiments have succeeded in their quest to create temperatures and densities similar to those found in the first few microseconds following the big bang. They have discovered a new form of matter with novel properties. An incisive program of measurements is underway to explore how the predictions of quark deconfinement and changes in the structure of the vacuum at high temperature are manifested in this matter.

A definitive measurement of the gluon contribution to the spin of the proton is made possible by the development of the world's only polarized proton-proton collider at RHIC, which has relied heavily on critical international funding contributions for its development.

- **A QCD-driven search for exotic particles, the imaging of quarks inside protons, and precise measurements sensitive to new physics are core components of the CEBAF 12-GeV Upgrade program. This upgrade should proceed as quickly as possible.**

New results from CEBAF have significantly enhanced the scientific case for the 12-GeV Upgrade. A new experiment to discover a family of predicted particles will improve our understanding of the confinement mechanism of quarks. High precision studies of electroweak symmetries may reveal new physics and will complement studies at high-energy colliders. Tomography of the structure of the nucleon's quarks and gluons will for the first time provide a visual image of their location and motion. These advances will profoundly deepen our understanding of the origins of mass and nuclear spin.

- **RIA remains the highest priority of our field for major new construction.**

The subcommittee reaffirms the compelling scientific case for the study of rare isotopes. RIA will address fundamental questions concerning the nature of nuclei and the origin of the elements. Scientific developments since the 2002 LRP have further strengthened this case. The timely completion of RIA is critical to U.S. nuclear science capabilities. However, the budget realities since the 2002 LRP have delayed an expeditious start to this world-leading facility, though not yet beyond the time scales historically characteristic of the intervals from LRP recommendation to start of major construction for CEBAF and RHIC.

The subcommittee continues to be guided by the 2002 LRP, following the recommendation that RIA can proceed only with a significant influx of new funding to prevent premature termination of world-leading science programs at CEBAF and RHIC. Nevertheless, the long term vision of our community is to pursue this compelling science with a major investment. The questions related to the nature of nuclear matter, the creation of new isotopes and elements, and the understanding of the origin of the elements demand a facility with the capabilities of RIA.

Investments in large-scale facilities in Japan and Europe underscore the world's assessment of the value of this science. An approach that advocates the large-scale use of these facilities by U.S. researchers addresses only some of the science, and would not lead to a robust U.S. program. Furthermore, facilities outside the U.S, already highly oversubscribed, do not have the capability to absorb a large U.S. program or to train the next generation of U.S. scientists needed for basic nuclear science research and national security. A 2004 NSAC subcommittee review concluded that the most powerful such facility is no substitute for RIA's unique reaccelerated beams and order-of-magnitude higher rare isotope intensities, both of which would provide unparalleled science capabilities.

Nuclear structure and nuclear astrophysics are at the core of nuclear science. The RIA facility is an integral part of the community's long-term plan for the future and it is premature at this stage to abandon this plan. In the current budget climate we recommend effective use of the current low energy U.S. facilities—with modest upgrades and novel instrumentation such as GRETINA, a DOE MIE—to remain at the science forefront in the near term. We further recommend continued investments in RIA R&D and planning. On a five-year time scale RIA must be well underway for the U.S. to lead in the future. If the budget situation does not improve in the next couple of years, the options for addressing this science must be fully reconsidered in the broader context of a new LRP for our field. These options would include: staged implementation of RIA; a smaller "niche" U.S. facility and/or significant investment in international options to address part of the compelling science; or the sacrifice of science at other forefronts of our field.

- **Nuclear physics has produced dramatic advances in neutrino science, with the demonstration of flavor change, mass, and oscillations. These discoveries open enormous opportunities in neutrino science, which represents a major priority for nuclear physics.**

The next steps toward a complete understanding of the role of the neutrino in nature are clear. We must learn whether neutrinos and antineutrinos are the same particle, which can be done only with experiments on neutrinoless double beta decay. Without the answer to this question, the fundamental new theory of matter cannot be completed. We now know that neutrinos contribute as much to the mass of the universe as stars do. But do neutrinos in fact have enough mass to shape the large-scale structure of the universe?

The mixing of neutrino flavors is central to understanding the role of neutrinos in astrophysics and cosmology, in particular in supernovae. It is also a key step on the road to finding an explanation for the matter-antimatter asymmetry of the universe. One of the mixing parameters, θ_{13}, is still unknown and could be directly determined or limited by sensitive oscillation experiments at nuclear reactors. The solar neutrino spectrum at higher energies has provided fundamental information about neutrino properties and confirmation of the standard solar model. Measurement of the solar neutrino spectrum at low energies will provide a direct and detailed test of our understanding of solar physics.

- **Nuclear physics initiatives in fundamental symmetry tests will open a window into physics beyond the standard model. These efforts test the very foundation of subatomic physics and must be pursued vigorously.**

New searches for the permanent electric dipole moments of the neutron and neutral atoms have outstanding discovery potential and will shed new light on the origin of the excess of matter over antimatter in the universe. Ultra-precise measurements of the decay of the neutron, properties of the muon, and weak interactions of electrons will probe energy scales that match—and in some cases, exceed—those reached in high-energy collider experiments. These measurements will provide new information about the symmetries present in the early universe.

- **The implementation of the recommendations of the NSAC Theory Report for increased investments in manpower and computing infrastructure is critical to the overall success of the nuclear science program.**

Research in nuclear theory continues to yield significant progress in all areas of nuclear science, with decisive impact on the experimental programs. The 2003 NSAC report, "A Vision for Nuclear Theory," identifies compelling scientific opportunities for the next decade and makes specific recommendations for increased support of theoretical research across all areas of nuclear physics. These include mechanisms for an increase in the theory workforce at universities and national laboratories and a sustained investment in multi-teraflop computing facilities to take advantage of opportunities in QCD lattice gauge theory, simulations of core collapse supernovae, and rigorous calculations of the structure of complex nuclei. These investments are essential for the success of the ongoing experimental programs and as a foundation for future initiatives; they should be implemented.

DOE and NSF have worked together for decades to optimize the U.S. nuclear science program. Clearly decisions made at either agency impact researchers at both. Indeed the National Superconducting Cyclotron Laboratory (NSCL)—a newly upgraded NSF facility—is a major component of the U.S. nuclear physics program. The subcommittee reaffirms the 2002 LRP priority given to the operation of the NSCL. The NSCL program is a key part of the world's rare-isotope research program having unique capabilities to study light r-process nuclei and light exotic nuclei near the neutron drip line. Its effective operation is essential for the U.S. program until the time when construction of RIA or an alternative with more advanced capabilities than the NSCL is underway.

The subcommittee offers another finding specific to the National Science Foundation:

- **A multipurpose deep underground laboratory, an NSF initiative, remains a high priority for nuclear physics research in the areas of neutrino physics and nuclear astrophysics.**

Exciting recent discoveries in neutrinos and astrophysics have been made in experiments sited deep underground, shielded from the rain of cosmic rays. Reducing backgrounds in future experiments in neutrino physics, such as double beta decay, and in nuclear astrophysics with accelerator beams at energies comparable to those found in stars will be extremely challenging. A deep underground laboratory will make these experiments possible, as well as opening research opportunities in several other fields of science and engineering.

NSF investigators have made substantial investments of equipment, through NSF supported Major Research Instrumentation grants, and manpower at both CEBAF and RHIC. Recent examples include contributions to the RHIC spin program—the STAR Endcap Electromagnetic Calorimeter—and two CEBAF experiments—Qweak and G0. Several years of running will be needed to obtain new science from the investments. Indeed, these contributions, like those from foreign countries, are made with the expectation that the opportunity will exist to carry out the subsequent science program.

As has been the case for many years, NSF investigators play a major role in carrying out the science program at all of the DOE nuclear science facilities and DOE scientists are making major contributions to the program at the NSCL. This synergy between DOE and NSF is valued highly in our field.

C. Budget Scenarios

NSAC has been asked to provide programmatic guidance at three budget levels. The specific request is:

> Your report should provide recommendations on the priorities for an optimized DOE nuclear science program over the next five years (FY 2007-2011), under the following scenarios:
>
> - Flat-flat funding at $370.4 million, actual dollars
> - Constant effort funding (starting with $370.4 million in FY 2006), inflated dollars
> - Funding levels needed to restore research capabilities and scientific programs to mount an optimized program and to address the scientific opportunities identified in the 2002 Long Range Plan in order of their priority.

The subcommittee is responding with a more comprehensive set of options. We have added two budget scenarios, both assuming a constant level of effort (yearly increases for inflation) for the next five years, with funding levels in FY07 which lie between the highest and lowest guidance levels indicated in the charge. The subcommittee, recognizing that long-term operation of a facility below about 50 percent of its capacity is neither cost-effective nor sustainable for an optimized program, finds that the two funding scenarios built on an FY06 budget of $370 M would force the closure of one of our two major facilities. We separately consider the action of closing either RHIC or CEBAF under such drastic budget strictures. Either option would result in tremendous loss of discovery potential and scientific productivity.

We begin with a budget that allows the basic components of the 2002 LRP to be executed, with the exception of construction of RIA. The budget profile needed to accomplish this is shown in **Figure V-1**. We have assumed that the President's budget request for DOE Nuclear Physics is enacted in FY06 in putting together this profile. Funding in FY07 would need to be increased to about $475,000,000 to begin implementing the plan. The budget proceeds to FY11 at a nearly constant level of effort, supplemented by incremental funding to support operations and detector upgrades at RHIC, and the CEBAF 12-GeV Upgrade.

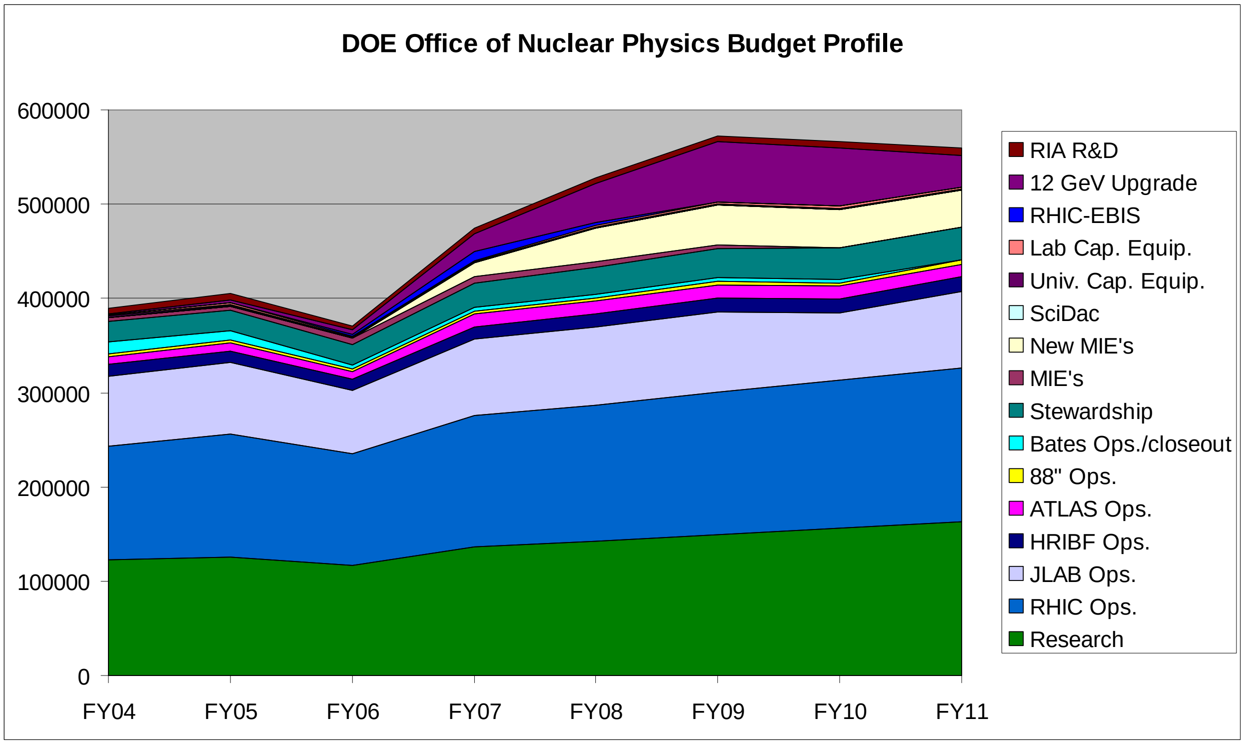

Figure V-1. The budget profile, in actual year-dollars, required to execute the basic components of the 2002 LRP, with the exception of the construction of RIA. RIA construction will require an increment to the budget. The vertical axis is in units of $1000.

The budget profile in **Figure V-1** provides funds to: operate our major facilities; increase support of research for university and national laboratory groups; carry out the 12-GeV Upgrade; initiate new experiments in neutrino science and fundamental symmetries; support detector upgrades at RHIC; increase support for nuclear theory; carry out upgrades at the two low-energy user facilities, ATLAS and HRIBF. This profile does not have funding for the construction of RIA and hence does not address the potential loss of leadership in this core component of the field, nor does it have funding for any of the major facility upgrades or new facilities that were mentioned as possible future initiatives beyond the basic recommendations in the 2002 LRP. The subcommittee believes that a major U.S. investment in support of the science of RIA must be made in the future, and therefore has continued RIA R&D funding to this end in all of its budget scenarios.

As budget levels are reduced from this $475 M, more sacrifices will be required. For all budget scenarios, the subcommittee recommends that funds remain in the program to: initiate new experiments in neutrino science and fundamental symmetries; increase support for nuclear theory; carry out upgrades at the two low-energy user facilities, ATLAS and HRIBF.

Under tighter budget scenarios, the subcommittee finds that implementation of a necessarily reduced version of the 2002 LRP still requires a combination of running the program and investment in the future. A budget based on an FY07 appropriation of $450 M and constant level of effort would slow considerably the progress in executing the basic program outlined in the LRP. Priorities within the relativistic heavy-ion program would be guided by the recent

Barnes report, "U.S. Program in Heavy-Ion Nuclear Physics: Scientific Opportunities and Resource Requirements." But the budget guidance may have to be modified from that considered in the Barnes Report, to permit suitable parallel progress on other fronts. The subcommittee views the future program at 12 GeV to be the highest priority for JLab and recommends that it proceed as quickly as possible. However, without incremental funding increases in FY08-FY11, the 12-GeV Upgrade may have to proceed more slowly, in a staged approach and at the expense of 6 GeV running.

A budget level based on an FY07 appropriation of $430 M and constant level of effort through FY11 is essentially identical to an inflation corrected budget projected from the FY05 appropriation ($404 M). The reduction from $450 M to $430 M in FY07, projected to FY11, seriously impacts the program. But the basic priorities remain the same. The CEBAF upgrade will be slowed even more. This may require forgoing operation of the 6 GeV program for much of the period between FY07 to FY11. Even with this reduction, operations and detector upgrades at RHIC will be more severely impacted than at the $450 M level, upgrades at ATLAS and HRIBF would be slowed and funding for new initiatives in neutrinos and symmetries would be stretched. Alternative solutions—run the 6 GeV program between FY07 and FY10 and then phase out operations at CEBAF or phase out RHIC to both operate and upgrade CEBAF—were not considered acceptable to the subcommittee.

Our nation has invested heavily in two facilities, CEBAF and RHIC, which are unique in the world and at the height of their productivities. The science opportunities at both facilities have attracted and continue to attract significant foreign participation and investments. However, it is imperative that we establish a stable funding environment for this to continue. If our major facilities are shut down with little or no notice, we cannot expect foreign colleagues to continue to convince their funding agencies to partner with us.

The subcommittee considered the $430M FY07 level budget scenario above to be a worst-case option for our field. The first two budget levels presented in the charge to NSAC—a new base level at the President's FY06 request and either flat-flat funding or constant level of effort to FY11—fall far below this and, if implemented, would produce ***disastrous consequences*** for our field. In either of these funding scenarios, operations must be curtailed at one of our two major facilities—CEBAF or RHIC—in the very near future. Either option would result in a loss of world-class science—science that simply could not be replicated elsewhere. It would abrogate international inter-laboratory agreements, seriously reduce the number of nuclear scientists that would be trained in the future and disenfranchise roughly 1/3 of the nuclear science community. The ripple effect in providing a future trained work force to deal with issues such as stockpile stewardship, homeland security, nuclear power and nuclear medicine could be enormous.

In the flat-flat scenario, the effective nuclear science budget would be reduced, due to inflation, by over 25% in FY11 relative the FY05 appropriation. The diminished prospects of carrying out world-class science would lead to a precipitous drop in the number of post-doctoral research associates and graduate students. In addition to the immediate impact, their numbers would continue to fall due to reduced opportunities to carry out world-class science and the availability of post-doctoral positions. While difficult to predict quantitatively, it is likely that the Ph.D. production would be at least cut in half by FY11 under this draconian budget.

The constant effort scenario starting with the FY06 request as a base would have a similar large impact on graduate students and post-doctoral research associates over the next few years with the closure of a major facility. Following an initial shock and subsequent drop in new student interest, we could hope that Ph.D. production would improve to something close to 2/3 of the present levels by FY11. This assumes a simple scaling based on the loss of research capabilities in the field.

However, we note that the effects of the loss of a major facility would extend far beyond the projected reductions in Ph.D. production. University research groups are a cornerstone of the national research program, since they provide the doorway for young people to enter the field of nuclear physics. Thus, the vitality of these groups is a significant factor in attracting and retaining young nuclear scientists. Nurturing and strengthening the technical infrastructure in nuclear physics at U.S. universities was identified as a top priority in the 2002 LRP. The sudden loss of one of the major flagship facilities would tear the very fabric of the university research effort and would have a very detrimental effect on staffing and morale.

The options of a CEBAF or RHIC closure, necessitated by these stringent budgets, were considered by the subcommittee and are detailed separately below. We start with the option of closing RHIC at BNL, labeled option A and continue with option B which discusses closing CEBAF at JLab.

Under option A, operations at RHIC would be terminated, starting in FY07. The AGS and booster could be supported for a small nuclear physics program and for running beams for NASA tests. The remaining funds from the RHIC closure would be allocated to the 12-GeV Upgrade, low-energy accelerator operations and upgrades and new MIE grants. In the flat-flat funding scenario, the 12-GeV Upgrade would stretch out to at least FY13 and no new initiatives could be accommodated before FY13-14. With the constant effort budget, the 12-GeV Upgrade would be completed earlier, before the end of FY13, and significant funding for a new initiative would be available in FY10.

Following a short run in FY06, scenario A would kill the RHIC program while it is still in its discovery phase. Of course the science *yet to be discovered* at RHIC is impossible to list. In broad terms, the science that we *know* would be lost includes:

- No further investigation of the new state of matter found at RHIC
- No real understanding of the QCD phase transition in the early universe
- Only minimal understanding of the gluon contribution to the proton spin
- No understanding of the sea-quark contribution to the proton spin
- No further investigation of QCD at truly high gluon densities.

Without the RHIC program, heavy-ion running at the LHC will face difficulties in producing a definitive understanding of the QCD phase transition or the new state of matter discovered at RHIC. The short running time for the heavy-ion program and the lack of proton-heavy ion collisions at the LHC greatly hinder the pursuit of baseline data so necessary for the systematic investigations of new phenomena. Furthermore, with its very different energy density, the LHC might not even replicate the new state of matter found at RHIC. It is crucial to also note that while a limited relativistic heavy-ion program would continue at the LHC, the spin program at

RHIC would die. The high-energy polarized proton-proton collider is unique—it simply could not be reproduced at the LHC.

Under option B, operations at CEBAF would be terminated, starting in FY07. Limited running would be available in FY06. The 6 GeV program at CEBAF would then be terminated and no option for an upgrade to 12 GeV would be left. The world would lose its most precise tool to probe QCD in nucleons and nuclei. In this scenario, the RHIC program would continue to run, albeit at reduced levels from FY05, and detector upgrades would continue. Work aimed at adding electron cooling to increase heavy-ion beam luminosities would proceed. Funds from the shutdown of CEBAF would go toward RHIC operation, low-energy accelerator operations and upgrades and new MIE grants. In the flat-flat funding scenario, funds through FY11 would be insufficient to undertake any new initiatives. In a constant effort scenario, a modest new initiative could begin to ramp up in FY08. The flexibility for operations and major new initiatives beyond FY11 within the field would be more constrained than in option A as the operations budget for RHIC is still higher than that projected for the upgraded CEBAF.

With option B, termination of the CEBAF program in FY07 would result in an enormous loss of science from the ongoing 6 GeV program and it would kill the science program and discovery opportunities of the 12-GeV Upgrade. Science that simply would be lost includes:

- No tomographic map of the quark and gluon content of the proton
- No discovery of new exotic particles predicted by lattice QCD
- No precision tests of the electroweak standard model
- No complete view of the strange quark contribution to the electromagnetic properties of the proton
- No understanding of how the properties of protons and neutrons are modified in nuclei.

No other facility in the world can recover the science lost by a termination of the CEBAF program at JLab. It will simply not be done.

RHIC and CEBAF are *the* two premier facilities for studying QCD in the world. They are complementary in their approach, covering very different aspects of the theory. And both are needed to develop a coherent picture of QCD. The subcommittee spent considerable time deliberating the merits of the two facilities in order to develop an answer to the charge for the lowest two budget scenarios. The subcommittee was faced with a deeply unsatisfactory choice. We should remember that in 2000, NSAC was asked to provide a coordinated framework for the future of the field. If RHIC continues to run under these constant-dollar levels, it will eventually dominate the nuclear science budget to an extent that makes it difficult to imagine a balanced future for the field of nuclear science. If on the other hand one closes RHIC now, the field will have increased flexibility for the future beyond FY11 by sacrificing its greatest present opportunity. After extensive and often painful discussion, we arrived at the following statement:

- Decades of careful planning and domestic and foreign investment into unique facilities have resulted in many important discoveries and remarkable payoffs. The subcommittee recognizes that under either scenario, the nation and its foreign partners will suffer a tremendous loss in science and the U.S. will no longer be able to maintain international leadership in at least one of the subfields of nuclear science. Because of the superb science lost in both scenarios, the committee was not able to make a choice based on scientific merit alone. The present budget scenario, however, represents a crisis that would preclude running both large facilities simultaneously and force an immediate choice while RHIC is still in its initial discovery phase. Based on this additional consideration, the subcommittee, while split in its decision, has a slight preference for the choice that maintains operations at RHIC. If such a budget exercise were to occur in the future, for instance, with the Jefferson Lab 12-GeV Upgrade well underway, a different choice might well be made.

D. Conclusions

If the budget projections that require closing CEBAF or RHIC, and abandoning plans for RIA become reality, U.S. nuclear science will suffer an extraordinary loss of discovery potential. But the message that this will send to potential future nuclear scientists may be even more damaging to the country in the long run. If our field must downsize in the future, it will. But closing one of our two major facilities now to achieve this will not make for a smooth transition. Clearly downsizing has long-term implications for the training of future scientists. Is there a vision of the future where nuclear scientists are no longer needed to deal with issues related to homeland security, nuclear proliferation, nuclear power and nuclear medicine?

A constant effort budget at the FY05 level would preserve the core facilities in our field but sacrifices would need to be made in all sectors to accommodate this. A compromise between the budget needed to implement the 2002 LRP and an FY05 base with constant effort would allow the field to maintain the present momentum preserving our two unique facilities so that they can fulfill their science missions.

The field of nuclear science has a clear vision, outlined by the 2002 LRP, of a future providing a balanced attack on our three major intellectual frontiers: the physics of QCD, the physics of nuclei, and physics beyond the standard model. Achievement of a smooth transition to that future will require major investments in new facilities within the coming decade. If the presently projected constrained budgets continue, the optimal way to arrange the desired transition will have to be the subject of a new long-range planning process in the nuclear science community.

Acknowledgements

Many members of the nuclear science community put in long hours on very short notice to provide the subcommittee with superb presentations at the Bethesda meeting and additional supporting material on which the science sections in the report are based. Without their help, this report would not have been possible.

The chair wants to especially thank Professor D. Hertzog and Ms. Celia Elliot for their help in editing the report. Finally, the chair expresses his gratitude to the subcommittee members. They were very professional in their approach to this extremely difficult task and they worked extraordinarily hard to produce this report.

A. Charge to NSAC

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

March 14, 2005

Professor Richard F. Casten
Chairman
DOE/NSF Nuclear Science Advisory Committee
A.W. Wright Nuclear Structure Laboratory
Yale University
New Haven, CT 06520

Dear Professor Casten:

In 2002, the Nuclear Science Advisory Committee (NSAC) completed work on a Long Range Plan for nuclear science for the decade. This plan recommended, with highest priority, the exploitation of the opportunities for scientific discoveries made possible by recent investments – especially at the new facilities, the Relativistic Heavy Ion Collider (RHIC), Continuous Electron Beam Facility (CEBAF) and National Superconducting Cyclotron Laboratory (NSCL). Funding above the FY 2001 constant-effort level (+15%) was identified as needed to effectively utilize the program's facilities and mount strong university and theory programs. In addition, the plan recommended the development of new research capabilities that required funding above this funding level. These included construction of a world-class Rare Isotope Accelerator (RIA) facility, construction of the world's deepest underground laboratory and the upgrade of CEBAF to 12 GeV.

Since the issuance of the Long Range Plan, the resources needed to implement the recommended program have not been identified by the agencies. In the FY 2002-2005 period, funding for the Department of Energy (DOE) Nuclear Physics program has been at a near constant-effort level. The FY 2006 President's Budget Request for Nuclear Physics of $370.4 million is an 8.4% reduction from FY 2005 Appropriations ($404.8 million). At this funding level, the Nuclear Physics user facilities will operate at ~65% of optimum operations and there will be a ~10% reduction in the number of researchers and graduate students supported by the program. This funding level, projected into the outyears, is not sufficient to maintain the scope of the present Nuclear Physics program and, in particular, to continue operations of the program's two major facilities, RHIC and CEBAF, as they are presently conducted. The major initiatives recommended in the Long Range Plan, such as RIA, are not accommodated. In light of these projected budgetary stringencies and their implications for the U.S. Nuclear Physics program, the priorities and recommendations of the 2002 Long Range Plan need to be revisited. A strategic plan on how to implement the highest priority science in the context of available funding and world-wide capabilities needs to be developed.

In FY 2005 the DOE Nuclear Physics program has world-leading research efforts in the major areas of nuclear science. NSAC should examine the existing research capabilities and scientific efforts, assess their role and potential for scientific advancements in the context of international efforts and determine the time and resources (the facilities, researchers, R&D and capital investments) needed to achieve the planned programs. NSAC should then identify and evaluate the scientific opportunities and options that can be pursued at different funding levels for mounting a world-class, productive national nuclear science program.

Your report should provide recommendations on the priorities for an optimized DOE nuclear science program over the next five years (FY 2007-2011), under the following scenarios:

- Flat-flat funding at $370.4 million, actual dollars
- Constant effort funding (starting with $370.4 million in FY 2006), inflated dollars
- Funding levels needed to restore research capabilities and scientific programs to mount an optimized program and to address the scientific opportunities identified in the 2002 Long Range Plan in order of their priority.

The report should discuss what scientific opportunities will be addressed, and what facilities and instrumentation capabilities will be used and developed by the DOE Nuclear Physics program, including those supported by the National Science Foundation and outside the United States, in mounting a productive, forefront program at each of the funding scenarios. For each funding scenario, the report should articulate what scientific opportunities and capabilities can and cannot be pursued, the impacts on training nuclear scientists, and how major initiatives such as RIA should be viewed.

NSAC should submit the report by the end of June 2005. We are aware that this is a difficult task. However, the involvement and input of the research community is essential for decisions that would restructure the nuclear physics portfolio in times of fiscal constraint. Your report will provide critical guidance as we go forward.

Sincerely,

Raymond L. Orbach
Director
Office of Science

Michael S. Turner
Assistant Director
Directorate for Mathematical
and Physical Sciences

cc:
Bradley D. Keister, NSF
Joseph Dehmer, NSF
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B. Charge to Subcommittee

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OFFICE OF THE DIRECTOR

3 May 2005

Robert Tribble
Cyclotron Institute
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College Station, TX 77843

Dear Bob,

As you know, Ray Orbach, Director of the Office of Science at DOE and Michael Turner, Assistant Director for the Directorate of Mathematical and Physical Sciences at the NSF, have charged NSAC to identify and evaluate the scientific opportunities and options for nuclear science in light of DOE budgets that have fallen short of those envisioned in the 2002 Long Range Plan for Nuclear Science. These shortfalls have been exacerbated in the FY 2006 President's Budget Request and projections for the outyears. The charge letter states that these budgets would not be sufficient to maintain the scope of the present Nuclear Physics program. Moreover, within these budget projections, the major initiatives recommended in the Long Range Plan, such as RIA, are not accommodated.

In light of the projected budgetary stringencies and their implications for the U.S. Nuclear Physics program, the priorities and recommendations of the 2002 Long Range Plan need to be revisited. The charge letter notes the need to develop a strategic plan on how to implement the highest priority science in the context of available funding and world-wide capabilities, and asks for NSAC guidance in this process.

The charge, of which you have a copy, contains three specific budget scenarios for the years 2007-2011: flat, constant dollar funding at the FY 2006 President's Budget; constant level of effort funding based in the FY 2006 budget; and funding levels needed to restore research capabilities and scientific opportunities identified in the 2002 Long Range Plan.

I am writing to formally ask you to serve as the Chair of an NSAC subcommittee to consider this charge and to report back to NSAC. The work of this subcommittee is of the utmost importance for the future of nuclear science in the U.S. for the foreseeable future. Decisions made now will have repercussions for decades and will affect not only research discoveries and future discovery potential but the stature of U.S. nuclear science on the

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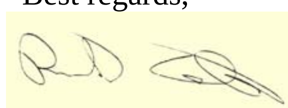
international level and the ability of nuclear science research and training efforts in this country to supply future national needs. The work of your subcommittee is likely to impact nuclear science in the U.S. for a generation.

As you know the timescale is very short since the Agencies have requested a report by June 2005. In order for NSAC to make an informed assessment of this uncommonly difficult charge I would like to ask you to send me your report no later than June 8, 2005 so that it can be carefully considered by NSAC in anticipation of a currently planned NSAC meeting on June 15, 2005.

I realize the burden and responsibility this puts on you and your subcommittee but can only say that it is an extraordinarily important task. Regardless of the outcome, I and our whole community will owe you an enormous debt of gratitude. I just want to express in advance my personal appreciation to you that you have agreed to take on this responsibility. I will be available to help you in any way I can and will attend the subcommittee meetings in an ex officio capacity.

Best regards,



Richard F. Casten
Chair, NSAC

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D. Meeting Agenda – Bethesda, MD.

Sunday, April 3, 2005
Morning
8:00 Executive Session
8:30 Agency Reports
11:30 Executive Session
12:30 Lunch

Afternoon – CEBAF presentations
1:30 L. Cardman "6 GeV science"
2:45 S. Chattopadhyay "6 GeV operations"
3:15 Break
3:30 P. Stoler "Users perspectives"
3:45 A. Thomas "12GeV upgrade and beyond"
5:00 C. Leemann "Summary and Conclusions
5:15 Executive Session until 8 pm

Monday, April 4, 2005
Morning – RHIC presentations
8:00 P. Chaudhari "Directors remarks"
8:15 S. Aronson "Overview"
8:55 M. Gyulassy "RHI questions"
9:20 R. Jaffe "Spin questions"
9:45 Break
10:00 J. Nagle "Experiment status"
10:30 A. Drees "Detector strategy
10:55 T. Roser "Facility strategy"
11:20 T. Ludlam "Budget"
11:50 TBD "Summary"
12:15 Executive Session and lunch

Afternoon
2:00 Nuclear Theory Center (W. Haxton)
2:45 Overview of Nuclear Theory (B. Mueller)
4:00 Nuclear Structure (R. Jannsens)
5:00 Executive Session until 8 pm

Tuesday, April 5, 2005
Morning
8:00 Nuclear Astrophysics (M. Wiescher)
9:00 Neutrons and Fundamental Interactions (B. Filipone)
10:00 Neutrinos and Double β decay (S. Freedman)
11:00 Executive Session and lunch
Adjourn at 4:00 pm