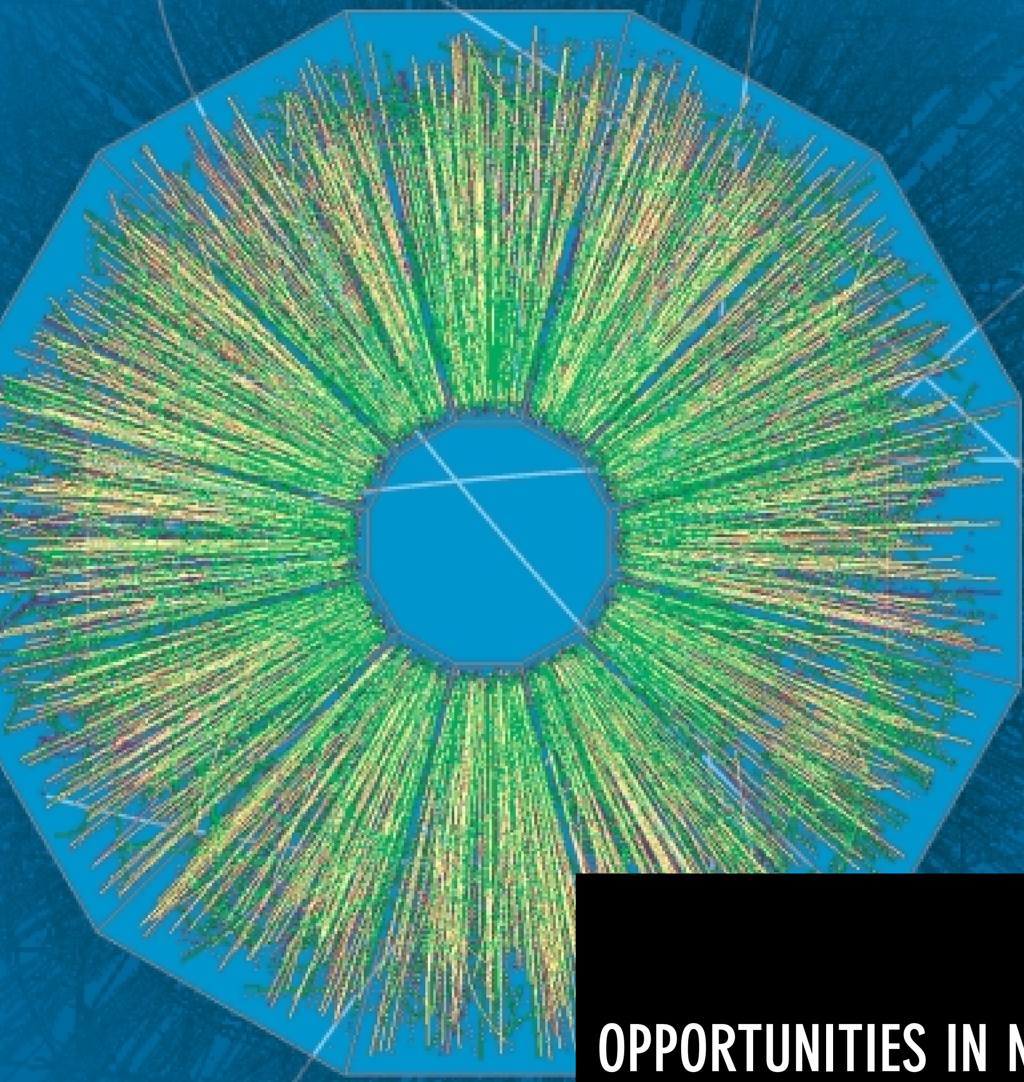

OPPORTUNITIES IN NUCLEAR SCIENCE

A Long-Range Plan for the Next Decade

April 2002

The DOE/NSF Nuclear Science Advisory Committee

U.S. Department of Energy • Office of Science • Division of Nuclear Physics

National Science Foundation • Division of Physics • Nuclear Science Section

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The Nuclear Science Advisory Committee

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Preface

The DOE/NSF Nuclear Science Advisory Committee of the Department of Energy and the National Science Foundation is charged with providing advice on a continuing basis regarding the management of the national basic nuclear science research program. In July 2000, the Committee was asked to study the opportunities and priorities for U.S. nuclear physics research, and to develop a long-range plan that will serve as a framework for the coordinated advancement of the field for the next decade. The plan contained here is the fifth that has been prepared since the Committee was established. Each of the earlier plans has had substantial impact on new directions and initiatives in the field.

NSAC is indebted to the Division of Nuclear Physics of the American Physical Society for organizing a series of four topical Town Meetings in late 2000 and early 2001. These meetings provided a forum for community input into the planning process and resulted in the production of White Papers that provide the scientific underpinning of this plan. A fifth White Paper on Education, covering the breadth of the field, was also written during this time.

A Long-Range Plan Working Group (see Appendix) including the Committee members and additional representatives from the nuclear science community was formed to determine overall priorities for the field. The working group met in Santa Fe, NM during the week of March 25 , 2001. During this meeting, the scientific opportunities and priorities were discussed in depth and consensus was reached on the prioritized recommendations contained in this report.

This report was prepared by the members of the Long-Range Plan Working Group. However, many others, too numerous to mention individually, contributed to the final document either as authors or readers. The chairman wishes to thank Douglas Vaughan, our technical editor, for his tireless efforts to create a coherent document.

The Committee is indebted to all the members of our community for their support of the planning process.

Executive Summary

Nuclear science is a key component of the nation's research portfolio, providing fundamental insights into the nature of matter and nurturing applications critical to the nation's health, security, and economic vitality. It is a field with tremendous breadth that has direct relevance to understanding the evolution of matter in the universe. Nuclear scientists today use sophisticated experimental and theoretical tools to probe the properties of nuclei and nuclear matter and of their ultimate constituents—quarks and gluons. At the same time, nuclear science is probing key interdisciplinary questions: the basis of fundamental symmetries in nature, how matter emerged in the first moments of the universe, the nature of supernovae, and the origin of elements in the cosmos. Nuclear science continues to have significant impact on other fields. The field is also a prolific source of today's technological work force. More than half of nuclear science Ph.D.'s apply their training outside their field—notably, in medicine, industry, and national defense.

The long-range plan for nuclear science that follows includes descriptions of recent progress across the full range of the field. One discovery, however, merits particular attention. Remarkable new measurements show that neutrinos produced by the nuclear reactions that power the sun change their character on their 93-million-mile journey from the solar core to the Earth. This result is a critical vindication of the theory of energy production in the sun: We now understand quantitatively what makes the sun shine. The transformation of neutrinos requires that they have mass, generating new questions at the same time old ones are resolved. The Standard Model of elementary particles provides no mechanism for neutrino mass and thus must be modified. In addition, theories of the evolution of the universe and the nature of the missing dark matter must take these discoveries into account.

This Plan has emerged from a process in which more than a thousand members of the nuclear science community participated by attending a series of public "town meetings," which led to the preparation of topical white papers. A smaller working group then prioritized the resulting recommendations. This Plan addresses the charge to NSAC to develop a "framework for the coordinated advancement of the field." The opportunities for such advancement are extraordinary, and addressing them will ensure the continuing vigor of nuclear science. The Plan includes the following four recommendations, which address critical funding issues facing the present program and guide new investments for the future:

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 new facilities, RHIC, CEBAF, and NSCL—which will greatly enhance the impact of the nation's 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. RIA is required 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 will 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 of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

In summary, nuclear science continues to address exciting and vital scientific questions and, thanks to recent investments, is poised for further great discovery. Implementation of this Plan will allow the field to maintain its world leadership position throughout the coming decade.

1. Overview and Recommendations

Nuclear Science Today

As we approach the centennial of Rutherford's discovery of the atomic nucleus, nuclear science remains a linchpin of the U.S. scientific enterprise. Indeed, with its scope enlarged by landmark astrophysical discoveries and by the successful formulation of a theory of subnuclear matter, nuclear science is more broadly compelling and more vital than ever before.

Nuclear science began by studying the structure and properties of atomic nuclei as assemblages of protons and neutrons. Research focused on nuclear reactions, the nature of radioactivity, and the synthesis of new isotopes and new elements heavier than uranium. Great benefit, especially to medicine, emerged from these efforts. But today, nuclear science is much more than this. Today, its reach extends from the quarks and gluons that form the substructure of the once-elementary protons and neutrons, to the most dramatic of cosmic events—supernovae.

The existence of quarks and gluons was first inferred from the spectrum of elementary particles and from electron-scattering experiments; subsequently, a new theory, quantum chromodynamics (QCD), was developed to describe them. Just as the formulation of Maxwell's equations led to a quantitative understanding of electromagnetic phenomena in the late 19th century, so the development of QCD a century later has provided the theoretical foundation for understanding nuclear phenomena and is now central to much of contemporary nuclear research.

Nuclear science also plays a vital role in studies of astrophysical phenomena and of conditions in the early universe. At stake is a fundamental grasp of how the universe has evolved and how the elements of our world came to be—two of the deepest questions in all of science.

The broad scope of nuclear science today intersects with that of several other scientific disciplines. The Standard Model of particle physics—and its possible shortcomings—now lies at the center of much nuclear science research. And high-energy physics, nuclear physics, and astrophysics are now closely linked in efforts to investigate the structure and dynamics of cosmic phenomena and to understand the immediate aftermath of the Big Bang. From a theoretical and experimental perspective, strong parallels even exist between the structure of complex nuclei and nanostructures of interest in the emerging field of nanoscience.

The impact of the field can be seen not only in basic science, but also in nuclear medicine, nuclear power, national defense programs, and numerous practical applications, from smoke detectors to scanners for explosives.

The scientific agenda. Thanks to recent investments by the DOE and the NSF, nuclear science is poised to make major advances in the coming decade. Today, the field can be broadly characterized by five scientific questions that define the main lines of inquiry. We expect that these questions will continue to drive nuclear science in the coming decade. Chapter 2 devotes a section to each of these questions, describing recent achievements and identifying prospects for the future.

What is the structure of the nucleon? Protons and neutrons are the building blocks of nuclei and neutron stars. But we now know that these nucleons are themselves composite objects having a rich internal structure. Connecting the observed properties of the nucleons with the underlying theoretical framework provided by QCD is one of the central problems of modern science.

What is the structure of nucleonic matter? A central goal of nuclear physics is to explain the properties of nuclei and of nuclear matter. The coming decade will focus especially on unstable nuclei, where we expect to find new phenomena and new structure unlike anything known from the stable nuclei of the world around us. With new theoretical tools, we hope to build a bridge between the fundamental theory of strong interactions and the quantitative description of nuclear many-body phenomena, including the new and exotic properties we expect in unstable nuclei and in neutron stars.

What are the properties of hot nuclear matter? The quarks and gluons that compose each proton and neutron are normally confined within the nucleon. However, QCD predicts that, if an entire nucleus is heated sufficiently, individual nucleons will lose their identities, the quarks and gluons will become "deconfined," and the system will behave as a plasma of quarks and gluons. With the Relativistic Heavy Ion Collider (RHIC), the field's newest accelerator, nuclear physicists are now hunting for this new state of matter.

What is the nuclear microphysics of the universe? A great many important problems in astrophysics—the origin of the elements; the structure and cooling of neutron stars; the origin, propagation, and interactions of the highest-energy cosmic rays; the mechanism of core-collapse supernovae and the associated neutrino physics; galactic and extragalactic gamma-ray sources—involve fundamental nuclear physics issues. The partnership between nuclear physics and astrophysics will become ever more crucial in the coming decade, as data from astronomy's "great observatories" extend our knowledge of the cosmos.

What is to be the new Standard Model? The resolution of the solar and atmospheric neutrino puzzles by the Sudbury Neutrino Observatory (SNO) and Super-Kamiokande—the long-sought demonstration that our current Standard Model is incomplete—opens up possibilities for exciting discoveries in the next decade. One such possibility is the observation of neutrinoless double beta decay, which would signal the violation of a crucial Standard Model symmetry. Precision experiments by nuclear physicists deep underground and at low energies are proving to be an essential complement to searches for new physics in high-energy accelerator experiments.

Recent accomplishments. Nuclear scientists have made many important discoveries in the past decade, most of them made possible by investments in new instrumentation. Although these achievements have answered significant questions, many point directly to even deeper questions that define some of the field's highest priorities for the coming years. Some recent highlights, organized along the lines of the five questions posed above, include the following:

Revealing the internal structure of nucleons—A new generation of experiments, coupled with more sophisticated theoretical and computational techniques, has challenged earlier perceptions of nucleon structure. The importance of gluons has been emphasized by their rapidly growing density as the proton is probed with higher resolving power, and by the fact that quark spins alone account for only a fraction of the nucleon's overall spin. A sizable measured imbalance between antiquarks of different types suggests that π mesons play as important a role inside nucleons as they do in theories of nuclear forces. A new high-resolution spatial map of the proton points to an unexpected depletion of charge near its center, not yet explained by current models. Surprisingly, the traditional description of nuclear forces continues to account well for the charge distribution of the deuteron, even at subfemtometer distances where the internal structures of the neutron and proton overlap strongly.

Challenging traditional descriptions of the atomic nucleus—Exploration of the unknown regions of the nuclear landscape, toward the limits of nuclear existence, has begun. Studies of exotic nuclei point to drastic alterations of the nuclear shell model, a hallmark of our understanding for half a century. In very heavy nuclei, observations that they can sustain rapid rotation demonstrate unexpected stability against disruptive centrifugal forces and confirm that the path to "superheavy elements" goes through nuclei with deformed shapes. Striking evidence for phase transitional behavior in nuclei has emerged from observations of sudden changes with mass between spherical and deformed systems, and from evidence of changes between liquid and gaseous forms of nucleonic matter. Advances in theory, such as calculations with realistic forces in nuclei containing up to 10 nucleons—an achievement thought impossible just a few years ago—offer the promise of a unified description of the nucleus based on the theory of the strong interaction.

Searching for matter at extremely high energy density—The first year of RHIC data-taking has produced strongly self-interacting matter at energy densities more than 20 times that of atomic nuclei. Matter under such extreme conditions is believed to be in a new state—the quark-gluon plasma. The estimates of energy densities have come from measurements of the number and energies of produced particles. The observed "flow" of matter indicates that this energy is rapidly converted to nuclear matter that is under immense internal pressure. In addition, particles emitted at high momentum are considerably suppressed relative to the rate seen in proton-proton collisions—an effect occurring only if the interactions among the particles produced are very strong. These results provide a confirmation of the picture that originally motivated the field of ultrarelativistic nuclear collisions.

Probing the origin of the elements and the evolution of stars—Two long-term multidisciplinary efforts to develop standard models of Big Bang nucleosynthesis and of the sun have been validated in remarkable ways: The baryon-to-photon ratio derived from analyses of temperature fluctuations in the cosmic microwave background is in good accord with the Big Bang nucleosynthesis prediction, while the total high-energy solar neutrino flux agrees with the standard solar model prediction. Important advances have also occurred in our understanding of nuclear reactions that govern red giant evolution, novae, and supernovae. Improved measurements of $^{12}C(\alpha,\gamma)$ set the luminosity for Type Ia supernovae as cosmological candles and define the limits for the final fate of the Type II supernova core as a neutron star or black hole. Finally, nuclear measurements far from stability and a new generation of computational techniques have brought us closer to the identification of the r-process site, or sites, and to quantitative models for the production of the heavy elements.

Tracing the missing mass of the universe—Observations of the neutrinos produced in nuclear reactions in the sun have for many years raised doubts about how the sun generates energy: Models of the sun consistently predicted the number of solar neutrinos to be much greater than observed. The solar models were recently vindicated when the SNO and SuperKamiokande experiments found that solar neutrinos change their identity on the way to the Earth, implying that they have mass. This discovery has profound implications: It provides a key to the fundamental structure of the forces of nature, and it shows that neutrinos contribute at least as much mass to the universe as do the visible stars. On the basis of these results, together with measurements of nuclear beta decay, we also now know that neutrinos do not have enough mass to stop the expansion of the universe.

Nuclear science in the national interest. A 1999 survey of nuclear science by the National Research Council, *Nuclear Physics: The Core of Matter, the Fuel of Stars,* described the field as "one of the cornerstones of the nation's technological edifice." There are two broad reasons for such a conclusion. First, nuclear science has been and continues to be a fertile source of practical enhancements to the quality of modern life. Many essential parts of modern medicine, for example, including modern imaging techniques, radiotherapy for the treatment of cancer, and the widespread use of radioisotopes for therapy and diagnosis, have their roots in nuclear science. The development of nuclear power is another descendant of early nuclear research, and current efforts aim at developments that would address significant problems. Research focused on developing the technology for "burning" long-lived nuclear wastes in accelerators serves as a prominent example.

Second, nuclear science research is a prolific source of today's technological work force. About 8% of all physics Ph.D.'s in the U.S. are awarded in nuclear science. Many of these students continue to pursue research in the field at the nation's universities and national laboratories. But more than half apply their technical training in other fields: in medicine, in industry, in other areas of science and technology, and even in finance. In particular, nuclear scientists continue to play critical roles in areas of national security, including many leadership positions at the defense laboratories. Indeed, about 20% of recent Ph.D. recipients in nuclear science currently pursue careers in areas pertinent to national security.

The nuclear science community also plays an active role in the education of precollege and undergraduate students and in public outreach—efforts aimed at nurturing future scientists and ensuring a citizenry with a strong scientific background. The K–12 school population is an especially fertile field for encouraging innate curiosity about the world around us. The Nuclear Science Wall Chart, for example, was developed to help schoolteachers make nuclear science an integral part of the precollege curriculum. Several efforts are also directed toward enhancing the scientific literacy of the public-at-large.

On yet another level, nuclear science stands as one of the core pursuits of the human imagination. Understanding the nature of matter, the ways in which it interacts, the cosmic processes by which the material universe has evolved, even the nature of the universe in its earliest moments—these are the goals of modern nuclear science. It is hardly an exaggeration to say that we are ennobled by such a quest, or that the national interest is well served by it.

Nuclear Science Tomorrow

Building on earlier plans. NSAC prepared its first long-range plan in 1979. Since then, a new plan has been prepared roughly twice each decade. After five years, conditions inside and outside the field have typically evolved sufficiently for even the best thought-out of these plans to need updating: Major projects are completed, significant discoveries are made, and new opportunities are identified—all of which influence priorities. Nevertheless, there is much continuity among the plans, and to a large extent, each plan has built upon the last. From today's perspective, the four earlier plans, and the developments they brought about, appear as chapters in a coherent historical account of progress in nuclear science.

Perhaps the most visible result of previous plans has been the construction of two major new facilities that remain unique in the world. The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab was the top priority for new construction in the 1979 long-range plan. This major new facility commenced operation in 1995 and now provides electron beams of unprecedented intensity and quality for probing the inner structure of the nucleus and the nucleon. The second major facility, RHIC at Brookhaven, was first proposed in the 1983 plan; construction was completed in 1999. RHIC accelerates nuclei and collides them at the highest energies ever achieved in the laboratory. For a brief moment, each of these collisions creates energy densities that approach those of the universe in the first fraction of a second after the Big Bang.

The plans, and the strategic thinking they reflect, have also succeeded in large measure in optimizing the nuclear science program—maximizing scientific productivity and return on investment. They have also led, inevitably, to evolution in the nuclear science community itself. As experiments have become larger and more complex, national laboratories have become the preferred sites for most new facilities. However, successive long-range plans have emphasized the importance of continuing to provide adequate support for the remaining university facilities and for university users of the national facilities. University researchers are the lifeblood of the field, carrying out much of the research and educating the next generation of scientists. Adequate support of the infrastructure needed by these university researchers remains a critical issue today.

Each plan has recognized the importance of finding a proper balance between effectively operating existing facilities, supporting researchers, and investing in new facilities and new equipment. Establishing an optimal program with necessarily limited resources has led to retrenchments in some areas of nuclear science, to the closure of a number of facilities, and to reduced support of users and running time at facilities. The 1996 plan gave high priority to the operation of CEBAF, to completion of RHIC, and to the development of facilities for research with unstable beams, including an upgrade of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State, which was completed in 2001. These goals have largely been met, and the most important issue facing us is to ensure that future funding is adequate to obtain the scientific return these investments merit.

Approach and scope of this plan. Development of the present long-range plan followed earlier practice. The Division of Nuclear Physics of the American Physical Society organized a series of town meetings to identify opportunities in four broad subfields of nuclear science: (i) astrophysics, neutrinos, and symmetries; (ii) electromagnetic and hadronic physics; (iii) nuclear structure and astrophysics; and (iv) high-energy nuclear physics. More than a thousand members of the nuclear science community attended these town meetings. Each meeting identified the key questions to be addressed in the coming decade and prepared prioritized recommendations for new initiatives. These findings and recommendations were included in a white paper for each subfield. A fifth white paper was prepared on nuclear science education and outreach. In addition, in many cases, the proponents of individual initiatives wrote documents detailing the scientific opportunities of their projects.

To prioritize the resulting recommendations, a Long-Range Plan Working Group was formed, with membership representing the breadth of the nuclear science community. This group met in Santa Fe, New Mexico, in March 2001 to draft recommendations. In addition to the working group members, the meeting was attended by representatives of the DOE and the NSF and by invited guests from the international nuclear science community. The charge letter to NSAC, the membership of the Working Group, information on the town meetings, and the links to the white papers can be found in the appendix.

The road ahead: Nuclear science in the 21st century. In their charge to NSAC, the funding agencies requested a "framework for the coordinated advancement of the field," identifying the most compelling scientific opportunities and the resources that will be needed to address them. In this Plan, we describe scientific opportunities that address important questions in each of the five scientific arenas introduced above. Maintaining a vigorous program in each area requires a careful balance between effective operation of existing facilities and new investments. This careful balance is reflected in our four prioritized recommendations.

RECOMMENDATION 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 new facilities, RHIC, CEBAF, and NSCL—which will greatly enhance the impact of the nation's 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.*

An overall increase of 15% for the DOE and the NSF is required to obtain the extraordinary benefits that this field offers to the nation.

The research of approximately 2000 U.S. scientists is tied to the operation of national user facilities in the U.S. And yet, in the past year, these facilities ran at 15–45% below their optimal levels. The increase in operating funds would eliminate this shortfall and produce a dramatic increase in scientific productivity as a product of increased operating hours, improved reliability, and an enhanced ability to upgrade experimental equipment.

The increase in funding would be used to invigorate the university-based research groups that contribute strongly to the intellectual development of nuclear science. The total number of physics Ph.D.'s awarded in the U.S. has been declining in the past five years, with a somewhat more rapid decline in the number of nuclear science Ph.D.'s. Allowing this trend to continue will imperil our leadership position in nuclear physics research, as well as impede progress in such related areas as nuclear medicine and national defense.

The increase would also be used to significantly increase theoretical research, which has also suffered erosion in recent years. Theory currently accounts for less than 5% of total funding for nuclear science, in contrast to the 10% recommended in the first long-range plan. Experimentalists consistently emphasize the crucial role of theory research, a fact reflected in each of the town meetings. We identify several mechanisms for addressing this issue in the current Plan.

Investment in new facilities is equally important. Scientific goals continually change as we obtain new results and as new opportunities arise. If resources were directed toward operating our present facilities to the exclusion of pursuing new directions, our field would quickly stagnate.

Many new initiatives were discussed and assessed during the town meetings. However, the Long-Range Plan Working Group considered only those large enough to significantly impact resources available to a particular subfield of nuclear science or, in some cases, to our whole field. The list of these substantial initiatives was then divided into three categories: (i) small projects, several of which would be initiated during the planning period, even within the constraints of a tight budget; (ii) medium-sized initiatives, such as major facility upgrades; and (iii) projects of such a scale that they represent a major reshaping of the field. In any decade, we would expect no more than one project of this last sort to be initiated. Prioritization of the initiatives discussed at the Santa Fe meeting provided the basis for the next three recommendations.

RECOMMENDATION 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. RIA is required 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.

The scientific justification for RIA has three broad themes:

- Investigations into the nature of nucleonic matter. RIA will define and map the limits of nuclear existence and allow us to explore the quantum mechanical structure of the exotic many-body systems that may be found near those limits.
- A quest to understand the origin of the elements and the generation of energy in stars. RIA will provide key data, such as masses, lifetimes, and reaction rates, needed for a quantitative understanding of the important nucleosynthesis processes, especially the r-process, by which much of the material around us was produced.
- Tests of fundamental conservation laws. RIA's unique capabilities, including the ability to create exotic nuclei, which can then be trapped, will permit sensitive tests of basic symmetries and other important aspects of the electroweak interaction.

The key to achieving these goals is RIA's driver accelerator, which will be a flexible device capable of providing beams from protons to uranium at energies of at least 400 MeV per nucleon, with beam power greater than 100 kW. It will provide higher intensities of radioactive beams than any present or planned facility, worldwide. This wealth of isotopes promises a wide variety of applications in basic sciences, applied sciences, and medicine.

RECOMMENDATION 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 will position the U.S. nuclear science community to lead the next generation of solar neutrino and double-beta-decay experiments.

A National Underground Science Laboratory (NUSL) will house experiments not only to answer significant nuclear physics questions, but also to address key issues in the related fields of particle physics, astrophysics, and cosmology. A wider science program at NUSL is also anticipated, including research in geology and microbiology, and applied efforts relevant to industry and national defense. Many next-generation experiments in all these fields must be substantially more sensitive than current ones and thus require shielding that can only be provided by working at great depth underground. It is highly advantageous, therefore, that a new laboratory be deeper than existing facilities in Japan and Europe.

The Homestake mine in South Dakota offers an ideal location for NUSL, with available experimental sites between 2100 and 7200 meters (water equivalent) below the surface. A proposal for the development of NUSL at Homestake has been submitted to the NSF, and efforts are under way for the state of South Dakota to assume ownership of the mine. A second potential site, at San Jacinto in California, has also been identified.

RECOMMENDATION 4

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

The 12-GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

Favorable technical developments, coupled with foresight in the design of the original facility, make it feasible to triple CEBAF's beam energy from the initial design value of 4 GeV to 12 GeV (thus doubling the *achieved* energy of 6 GeV) in a very cost-effective manner. The timely completion of the CEBAF upgrade will allow Jefferson Lab to maintain its world leadership position, as well as to expand that leadership into new areas. The upgrade will provide an exceptional opportunity to study a family of "exotic mesons" long predicted by theory, but whose existence has only recently been hinted at experimentally. Equally important, the higher energy will open the door to the exploration, through fully exclusive reactions, of regions of high momentum and high energy transfer where electron scattering is known to be governed by elementary interactions with quarks and gluons.

Other initiatives. Even under the tightest budget constraints, a fraction of the nuclear physics budget must be set aside to provide the flexibility to fund smaller new initiatives. The following initiatives were identified by the Long-Range Plan Working Group as having great promise but were not prioritized. Those that may be accommodated within the existing budget will be implemented, while others, at earlier stages of development, may be promoted to the status of strong recommendations in a subsequent long-range plan.

- **RHIC II.** RHIC is currently the most powerful facility in the world for the study of nuclear collisions at very high energies. Nonetheless, a significant enhancement of the luminosity at RHIC, together with upgraded detectors, may be necessary to fully investigate the properties of nuclear matter at high temperature and density. The associated costs are incremental in comparison to the large investment already made in the RHIC program.

- **The Electron-Ion Collider (EIC).** The EIC is a new accelerator concept that has been proposed to extend our understanding of the structure of matter in terms of its quark and gluon constituents. Two classes of machine design for the EIC have been considered: a ring-ring option where both electron and ion beams circulate in storage rings, and a ring-linac option where a linear electron beam is incident on a stored ion beam.

  These first two initiatives, in particular, require ongoing R&D. For the field to be ready to implement the RHIC upgrade later in the decade, essential accelerator and detector R&D should be given very high priority in the short term. Likewise, there is a strong consensus among nuclear scientists to pursue R&D over the next three years to address a number of EIC design issues. In parallel, the scientific case for the EIC will be significantly refined.

- **4π Gamma-Ray Tracking Array.** The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array that would build on the success of Gammasphere is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions. This new array would be a national resource that could be used at several existing stable- and radioactive-beam facilities, as well as at RIA.

- **Neutron Initiative.** Intense beams of pulsed cold neutrons and beams of ultracold neutrons (UCNs) offer sensitive tools for testing fundamental symmetries and for elucidating the structure of weak interactions. Experiments are now under way with pulsed cold neutrons at LANSCE at Los Alamos, and in the future, we expect to take similar advantage of the Spallation Neutron Source (SNS), now under construction at Oak Ridge. In a second thrust, great advances have been made in the development of superthermal UCN sources. Such a next-generation high-flux source might be sited at a number of facilities, including the SNS. The opportunities at SNS represent a very highly leveraged use of nuclear physics funds to carry out world-class experiments with neutrons.

- **Large-Scale Computing Initiative.** Many forefront questions in theoretical nuclear physics and nuclear astrophysics can only be addressed using large-scale computational methods. High-priority topics include lattice QCD calculations, multidimensional supernova simulations, and quantum many-body calculations of nuclear structure. Theoretical work of this kind is crucial if we are to realize the full physics potential of the investments made at Jefferson Lab and RHIC, and the new investments recommended for RIA and NUSL. To exploit current opportunities, dedicated facilities must be developed with world-leading computational capabilities for nuclear physics research.

- **ORLaND.** The SNS at Oak Ridge will be not only the world's most intense pulsed neutron source, but also the world's most intense pulsed source of intermediate-energy neutrinos. This provides a unique opportunity to conduct experiments complementary to those that might be undertaken at NUSL. Accordingly, the Oak Ridge Laboratory for Neutrino Detectors (ORLaND) has been proposed. It would consist of a concrete "bunker" large enough to accommodate one very large (2000 ton) detector and five or six smaller special-purpose detectors, with an overburden of 30 meters (water equivalent) to further reduce the background from cosmic rays.

Resources. The long-range plan that we are proposing will require increased funding, first to exploit the facilities we have built, and then to invest in the new initiatives we have identified. At the same time, we recognize that there have been significant changes on the national scene since this planning exercise began. First, the response to the tragic events of September 11, 2001, is forcing a reassessment of national priorities in which the war on terrorism is given highest priority. Second, the current economic downturn is driving a careful evaluation of discretionary spending, with an understandable emphasis on short-term economic stimulus. Nevertheless, the scientific opportunities open to us are no less compelling than they were at the start of the planning process. We also firmly believe that basic research in fields such as nuclear science is crucial to the long-term health of the U.S. economy and to national security.

These issues have been discussed in many places, including the "Road Map for National Security: Imperative for Change," the final report of the U.S. Commission on National Security/21st Century, which recommends "doubling the U.S. government's investment in science and technology research and development by 2010." The report makes a number of thoughtful recommendations on the importance of investment in basic science, from which the "most valuable long-run dividends are realized," and on the way in which science priorities should be set at the national level. These critical national concerns are well captured in the words of Leon Lederman, Nobel Laureate and former Director of Fermilab: "The combination of education and research may be the most powerful capability the nation can nurture in times of stress and uncertainty."

It must be remembered, too, that, like many branches of the physical sciences, nuclear physics budgets at the DOE and the NSF have been eroded in recent years. For example, since 1995, when NSAC prepared its last long-range plan, the overall budget for nuclear physics within the DOE has declined by 8.4% when inflation is taken into account; in the same period, support for research has been cut by 15%, because of pressure to fund operations at the new facilities and to support important stewardship activities at the national laboratories.

Funding the long-range plan. The full cost of the proposed long-range plan over the next decade is discussed in Chapter 6 (and a funding scenario consistent with the plan is summarized in Figure 6.4). Some key fiscal features of the plan are the following:

- *Recommendation 1—Facility operations and research.* Our first recommendation can be addressed by a 15% increase in funding, above inflation, for the field (including both DOE and NSF programs). This increased funding level will enable us to take full advantage of the investments made in our field and to exploit the outstanding opportunities open to us.
- *Recommendation 2—Rare Isotope Accelerator.* RIA is our highest priority for major new construction. It will allow us to realize the outstanding scientific opportunities offered by research with rare isotopes and to ensure continued U.S. leadership in nuclear structure and nuclear astrophysics research. As noted in the detailed recommendation, construction of RIA will require significant funding above the nuclear physics base. Most of the current base funding in nuclear physics from the DOE supports researchers at universities and national laboratories, together with operation of our two flagship facilities, CEBAF and RHIC. Redirection of funds away from areas where we are reaping the scientific benefits of

recent investments would be inconsistent with our first recommendation. At the same time, the low-energy nuclear science community must be nurtured for RIA to be successful when construction is complete.

- *Recommendation 3—The National Underground Science Laboratory.* NUSL has been proposed to the NSF, with funding to start in fiscal year 2003. It will provide opportunities for several fields, including high-energy and nuclear physics, geophysics, terrestrial biology, and national security. The cost of constructing the laboratory and the initial complement of detectors requires additional funding above the nuclear physics base.
- *Recommendation 4—The Jefferson Lab Upgrade.* The Jefferson Lab Upgrade is included as a construction project starting in fiscal year 2005, leading into a modest increase for Jefferson Lab operations later in the decade.

Constant-effort budget. In our charge, we were asked to provide guidance for a constant-effort budget at the level of fiscal year 2001, throughout the years 2001–12. In recent years, NSAC has been asked to review priorities for two subfields of the DOE nuclear physics program: the medium-energy program in 1998 and the low-energy program in 2001. In each case, priorities were set for constant-effort budgets, balancing support for existing programs against new investment, and some retrenchments were recommended. In the event of constant-effort budgets for the next decade, similar exercises would be necessary for all subfields of nuclear science, and it is clear that further retrenchments would take place.

We have laid out a framework for coordinated advancement in each of the subfields of nuclear science. For nuclear structure and astrophysics, the centerpiece of this Plan is the construction of RIA. In the constant-effort scenario, the major new construction projects, RIA and NUSL, could not be built, as the required funding could not be found in the rest of the program. Without a new project such as RIA, the existing facilities in nuclear structure and astrophysics will, over the coming decade, become less competitive with overseas efforts in Europe and Japan, where substantial investments are being made. Similarly, without a facility such as NUSL, the U.S. will not be in a position to assume the leadership role that we envisage for the next generation of underground experiments.

We should emphasize that smaller initiatives—even medium-sized initiatives such as the Jefferson Lab Upgrade— should be accommodated within a constant-effort budget. However, the lost opportunity to build a major new facility, and the much slower pace of new initiatives, would be costly for the field.

The following pages describe in depth the opportunities and initiatives described in this overview and the resources that they will require. Chapter 2, comprising five substantial sections, offers a more detailed picture of nuclear science research today, together with a view of prospects for the future. Its five sections pursue the themes identified above in “The Scientific Agenda:” the structure of the nucleon, the structure of the nucleus, the properties of nuclear matter under extreme conditions, nuclear astrophysics, and the quest for a new Standard Model. In Chapter 3, we offer brief descriptions of today’s operating research facilities and, in Chapter 4, describe other facets of the nuclear science enterprise: its role in education and public outreach, its international and interdisciplinary aspects, and its impact on society. Chapter 5 provides in some detail our vision for the future of the field, embodied in the four major recommendations and the other initiatives outlined above. The Plan concludes in Chapter 6 with a description of the resources needed to realize this vision.

2. The Science

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Protons and Neutrons:

Structure and Interactions

Overview: QCD and the Structure of the Nucleons

Protons and neutrons are the seeds of all observable matter in the universe. The positively charged proton is the nucleus of the hydrogen atom, and protons and neutrons—the proton's uncharged analogs—are bound together to form all other atomic nuclei. A deeper layer to nuclear matter has also been uncovered: Protons and neutrons are composed of lightweight, pointlike quarks and gluons. These constituents possess another type of charge, known as color, which is the source of the powerful forces that first cluster the quarks and gluons to make protons and neutrons, and in turn grip these nucleons to one another, forming atomic nuclei. The fundamental theory underpinning all of these phenomena is known as quantum chromodynamics (QCD). A central goal of nuclear physics is to understand the structure and properties of protons and neutrons, and ultimately atomic nuclei, in terms of the quarks and gluons of QCD.

Quantum chromodynamics is similar in name to the well-known theory of electric charges and light—quantum electrodynamics (QED)—a similarity that reflects deep parallels between these two fundamental theories. Electric charges provide the forces that hold electrons in atoms, which in turn combine to make molecules; color charges provide the forces that build protons and neutrons, which in turn combine to make atomic nuclei—in a sense the "molecules" of QCD. However, there is a profound difference: Atoms can be ionized, and the fundamental electric charges of QED can appear in isolation, but in QCD the fundamental quark and gluon constituents of protons and neutrons cannot be liberated. They are said to be permanently confined. This property ultimately gives stability to matter as we know it.

While the mechanism of confinement within QCD is understood qualitatively, a quantitative understanding remains one of the greatest intellectual challenges in physics. The QCD theory implies, and experiment confirms, that when nuclear particles are studied at very high resolution, their constituent quarks and gluons act as almost free particles. Such resolution can be obtained in experiments at high energies, so-called hard-scattering experiments. (See "Hard Scattering," pages 18-19.) Such experiments have shown in detail how the energy and spin of the parent protons and neutrons are shared among their quark and gluon constituents. However, in lower-energy experiments, a global or "long-distance" picture is obtained. Here, the quarks and gluons are found to interact with one another exceedingly strongly, so strongly that their individual identities can become obscured. This powerful attraction is responsible for their confinement, and while QCD theory qualitatively implies that this should be so, complex nonlinear features of the theory make complete calculations impossible today.

Probing the nucleons: Recent achievements. Relating quark and gluon properties as measured in the high-resolution data to the more global properties of protons and neutrons revealed by lower-energy data—for which confinement dominates—is an outstanding problem. Consequently, models have been developed that strive to incorporate the important physics of QCD and thus to calculate experimental observables. Examples include effective field theories and models that invoke symmetries of QCD, such as chiral symmetry (see pages 46–47). Substantial progress is being made by use of large-scale computers, which perform detailed QCD calculations of nucleon properties using a discretized space-time lattice. These "lattice QCD" calculations have great potential to usher in a new era in understanding the fundamental structure of the proton and neutron.

These theoretical studies of QCD predict the existence of completely new physical phenomena that should be revealed under conditions hitherto inaccessible to detailed exploration. For example, when the nuclei of heavy elements collide at extreme energies, their neutrons and protons may effectively "melt," liberating the fundamental quarks and gluons as a form of plasma (see pages 51–52). Other novel consequences of confinement are predicted at relatively low energies, including new forms of matter known as "hybrids," in which the gluonic degrees of freedom are excited in the presence of the quarks. Establishing the existence or nonexistence of these hybrids and the quark-gluon plasma is of fundamental importance and will also provide new insights into the nature of confinement.

Nuclear physicists most often probe the strongly bound protons and neutrons using the electroweak interaction, the best understood process in nature. These experiments typically use beams of leptons (i.e., electrons, muons, or neutrinos) or photons over a broad range of energies to probe nucleon structure over many distance scales. Such experiments also provide especially sensitive ways of distinguishing the different "flavors" of quark, notably the up and down quarks that help to give protons and neutrons their separate identities. At low momentum transfers, static properties of the proton and neutron, such as their shape, size, and polarizability, are determined and compared with QCD-inspired models and lattice calculations. At high momentum transfers, the spatial, spin, and flavor structure of the proton and neutron are probed by scattering from the elementary quark and gluon constituents.

A view to the future. Over the past decade, a new generation of experimental capabilities has been put in place. High-duty-factor beams of electrons, polarized beams and targets, and revolutionary new detectors have become available, producing unexpected, and not yet fully understood, results. With these tools, we have gained new insights into proton and neutron structure. For the future, important new devices and capabilities are under development, including a pure, solid hydrogen or deuterium target (for experiments at the Laser Electron Gamma Source facility at Brookhaven) and intense polarized photon beams (the High Intensity Gamma Source facility at Duke). At MIT-Bates, the new Bates Large Acceptance Spectrometer Toroid, coupled with the intense, highly polarized electron beams and pure polarized-gas targets internal to the South Hall Ring, will provide high-precision data on nucleon structure at long distance scales. Each of these devices will add critical capabilities in the near future. In the longer term, the proposed 12-GeV upgrade of the CEBAF accelerator at Jefferson Lab will greatly extend the scientific reach of this facility and open new opportunities for the program. The hybrid mesons described above, for example, are expected to be produced by photon beams that will be available at an upgraded Jefferson Lab. A complete understanding of the fundamental structure of matter will require continued experiments over a broad range of energies and the continued development of new devices and capabilities.

The Building Blocks of Matter: The Structure of Protons and Neutrons

Detailed investigations of the structure of the proton and the neutron are essential for understanding how these basic building blocks of nuclear physics are constructed from the quarks and gluons of QCD. Remarkable new data are now becoming available that shed a revealing light on hadron structure, and yet much remains to be learned.

Elastic form factors of nucleons. The electromagnetic form factors of a nucleon provide a picture of the distributions of its charges and currents, due almost entirely to up and down quarks. High-energy hard-scattering data have shown that, in addition to these quarks, there are also antiquarks inside the nucleon, some of which are probably responsible for the nucleon's pion cloud, though the precise details have been unclear. Recent precision measurements of the electric and magnetic polarizabilities of the proton have now revealed the role of pions in nucleon structure. Data with comparable precision are still needed for the neutron, and available results are in serious disagreement with theory. Existing and planned low-energy facilities will be able to make extremely precise measurements for the neutron polarizabilities in the near future.

An experiment at Jefferson Lab has found that the charge and current distributions in the proton are not the same. By measuring the polarization of the outgoing proton in elastic electron scattering from a proton target, experimenters determined the ratio of the electric and magnetic form factors, G_E and G_M, respectively, with small systematic uncertainties. The data, depicted in Figure 2.1, show that G_E and G_M behave differently as the resolution of the "microscope" (the momentum transfer Q^2) increases.

Comparable precision measurements for the neutron are much harder, not least because a practical pure neutron target cannot be produced. The total charge of the neutron is zero, as the net contributions from its positively (mostly u) and negatively (mostly d) charged quarks counterbalance each other. However, within the neutron, there is a distribution of electric charge that has been revealed in recent years by a number of experiments using ^{2}H and ^{3}He targets, often involving polarization techniques. Results from experiments at higher resolution are expected shortly. New precision data on the magnetic structure of the neutron have also been obtained.

The high-energy hard-scattering data have shown that strange quarks and antiquarks ($s\bar{s}$) also play a role inside the nucleon, in particular by contributing to the spin of the proton and neutron. The question of how these strange particles cooperate in constructing the nucleon is currently being

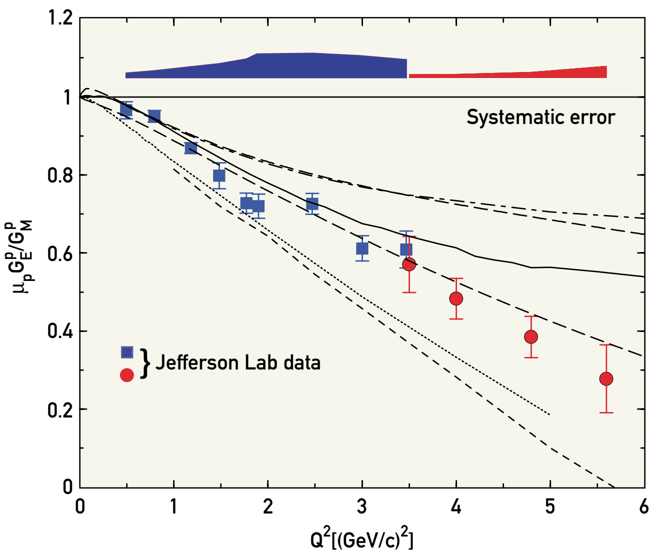


Figure 2.1. High-precision images of a proton's charge and magnetism. Old data could not tell if the electric and magnetic structures of the proton behaved in the same way, as resolution (Q^2) improved. New high-precision data from Jefferson Lab show conclusively that they do not, with the electric form factor (G_E^p) decreasing relative to the magnetic (G_M^p) as Q^2 increases. This implies that the proton's electric charge is suppressed relative to its magnetism for short distance scales; the proton's electric charge may even have a hole near its center.

investigated. Advances here are among the most important achievements since publication of the 1996 long-range plan. Determining the role of $s\bar{s}$ involves measuring the response of nucleons to both electromagnetic and weak interactions, in particular through measurement of parity-violation effects in electron scattering. These new parity-violation experiments, which represent major technical advances, complement measurements of the charge and current distributions in the nucleons by measuring the effect of the parity-violating neutral weak interaction between an electron and a quark in the nucleon.

The results of the SAMPLE experiment at MIT-Bates are shown in Figure 2.2, plotted as a function of the strange quark contribution to the magnetization, G_M^s, and the axial current, $G_A^e\,(T=1)$, for a particular resolution, $Q^2 = 0.1$ (GeV/c)^2. The overlap of data for hydrogen (diagonal band) and deuterium (inclined vertical band) defines the measured values of both form factors, indicating that the contribution of strange quarks to the proton's magnetism is less than 5%.

The HAPPEX experiment at Jefferson Lab has extended parity-violation measurements of the strange form factors to larger momentum transfer [$Q^2 \sim 0.5$ (GeV/c)^2]; here, too, the measured values are smaller than theory predicted. Planned experiments are expected to determine whether the small measured value arises from a cancellation of electric and magnetic contributions or from a cancellation of the s and $\bar{s}$ contributions in the nucleon itself. Other planned experiments will separate electric and magnetic contributions, as well as extend the data over the range $Q^2 \sim 0.1$–1 (GeV/c)^2.

Excited-state structure. Adding energy to the nucleon provides a complementary look at its structure. The quarks and gluons change configurations to form excited states, just as the nucleons and mesons do to form excited states of nuclei. Many modern QCD-inspired models attempt to describe the spectrum of these excited states, as well as their detailed structure. For example, many of these models predict that the lowest-lying excited state of the nucleon, the delta resonance, is photoexcited predominantly by magnetic dipole radiation, with electric quadrupole excitation becoming significant in high-resolution electroexcitation. An accurate measurement of the quadrupole excitation of the nucleon can thus be of great importance in testing the forces

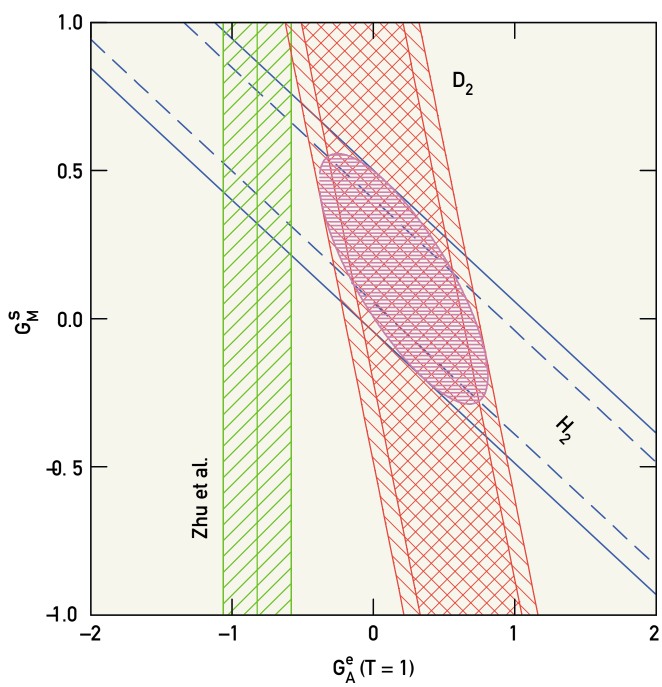


Figure 2.2. Results from the SAMPLE experiment at MIT-Bates on hydrogen and deuterium. The overlap of the data for hydrogen (diagonal band) and deuterium (inclined vertical band) defines the strange quark contribution to the proton's magnetic moment (vertical axis), which was previously unknown. It also determines the proton's axial charge as measured in electron scattering (horizontal axis), which is surprisingly far from the theoretical estimate (green band).

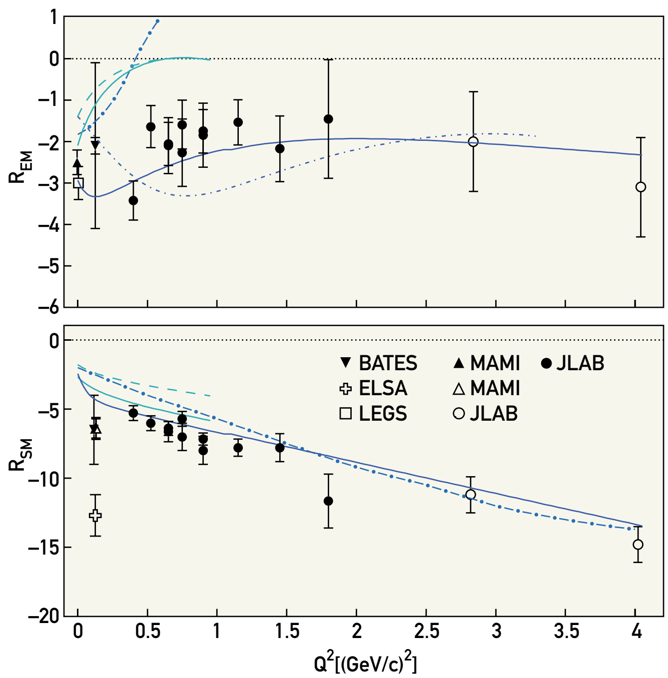


Figure 2.3. Data from LEGS (Brookhaven), MAMI (University of Mainz), ELSA (University of Bonn), MIT-Bates, and Jefferson Lab on the Q^2 dependence of the multipole ratios R_{EM} and R_{SM} for excitation of the delta resonance, the lowest-lying excited state of the proton. Curves show model calculations.

between the quarks and, more generally, models of the nucleon.

With the current generation of electron accelerators, the ability to carry out such experiments has advanced greatly. Recent data on two different measures of the nonmagnetic contributions to excitation of the delta, represented by the quantities R_{EM} and R_{SM}, are compared with theoretical calculations in Figure 2.3. The R_{SM} data tend to support the underlying QCD prediction that they be independent of Q^2 as $Q^2 \to \infty$. The R_{EM} data appear to discriminate among detailed models of the nucleon.

The spectrum of excited states of a system of bound particles exposes the underlying dynamics. Several excited states of the nucleon above the delta resonance have been observed, but they are hard to identify, as they are often broad and overlapping. The traditional quark model has described the spectrum rather well but predicts far more resonances than have yet been observed. It could be that the number of internal degrees of freedom is restricted; for example, if two of the quarks are bound in a diquark pair, the density of predicted resonances is lowered. An alternative possibility, predicted by the model, is that the missing resonances tend to couple strongly to the ρN, $\Delta\pi$, and ωN channels, which have not been amenable to precise measurement. Such measurements are beginning now with the CLAS detector at Jefferson Lab, with enhanced sensitivity afforded by the use of longitudinally polarized electrons and newly available linearly and circularly polarized photons, together with longitudinally and transversely polarized targets. An upgraded Jefferson Lab will enable these studies to be pursued to higher resolution.

Hard scattering and quark distributions. A detailed mapping of the quark and gluon constituents of the nucleon has been undertaken through hard scattering of electron, muon, or neutrino beams from protons or neutrons within light nuclei (see "Hard Scattering—Probing the Structure of Matter," pages 18–19). Since the presence of quarks and gluons was first inferred in hard-scattering experiments at SLAC in the late 1960s, many laboratories have contributed to current knowledge of the quark and gluon (collectively, the parton) distributions over broad ranges of Q^2, the momentum transfer, and of the fraction x of the proton's momentum that is carried by the struck quark. The dependence on Q^2 at larger momentum transfers is well understood within QCD. In order to understand the x dependence, it is advantageous to identify three distributions: those of (i) the "valence" quarks that determine the primary quantum numbers of the hadron (such as two up quarks and one down quark in the proton, or an up quark and a down antiquark in the π^+ meson); (ii) the sea of quark-antiquark pairs; and (iii) the gluons that provide the binding. The valence quarks dominate at high x; QCD predicts that as the Q^2 increases, the sea of quark-antiquark pairs and the gluons dominate the low-x region. Experiment has confirmed this.

The shapes of these three x distributions are the results of the strong interactions that confine the quarks and gluons in the hadron. Realistic QCD calculations of these distributions are only beginning, and most of what is known of them comes from experiment. Nuclear physics has long suggested that a proton spends part of its time as a fluctuation into a neutron and a π^+. The latter contains a down antiquark ($\bar{d}$), so this picture implies that the distribution of the $\bar{d}$ quarks will differ from that of the up antiquarks ($\bar{u}$) in the proton. One of the most dramatic recent results came from a measurement at the Fermilab proton accelerator; it showed (see Figure 2.4) that the distributions of $\bar{d}$ and $\bar{u}$ do indeed differ. This result demonstrates that the strong-interaction

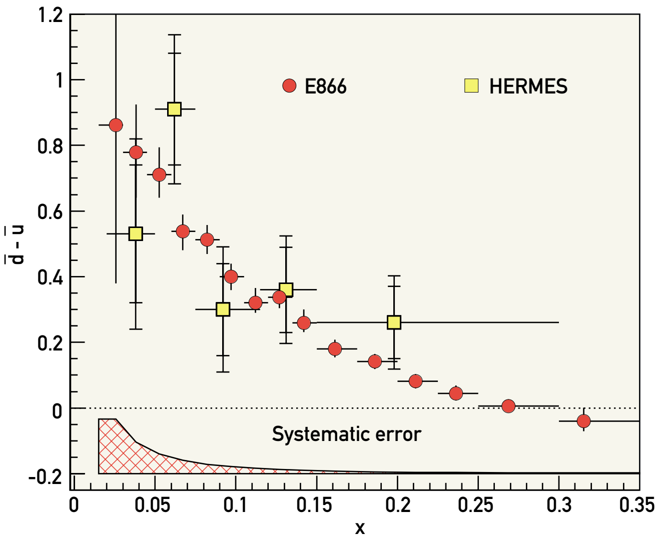


Figure 2.4. Data from HERMES (DESY) and E866 (Fermilab). The difference in the distributions of $\bar{d}$ and $\bar{u}$ antiquarks in the proton depends on the fraction x of the proton's momentum carried by the antiquark. The shape of this distribution signals the influence of fluctuations of the proton into a neutron and a π^+ meson.

regime of QCD is essential for understanding the antiquark distributions. These experiments have a direct bearing on other probes of the sea of quark-antiquark pairs, for example, the sea of strange quarks that are studied in parity-violating electron scattering.

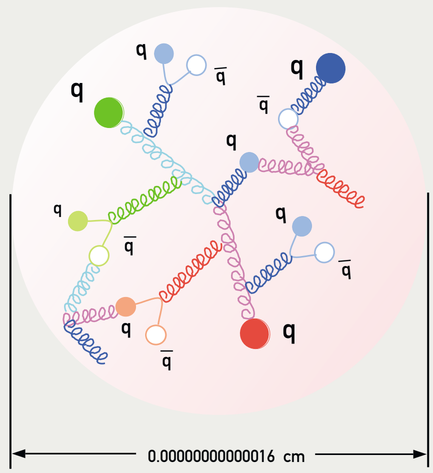
The biggest uncertainty in the parton distributions of the proton lies in understanding the distribution of the glue. As the resolving power of a nucleon probe gets finer (or, equivalently, as Q^2 gets larger), the number of gluons is found to grow substantially. Experiments show that approximately half of a nucleon's mass and half of its momentum are due to the gluons, rather than the quarks. Hadron-hadron collisions are especially sensitive to the glue, and the determination of the gluon distributions of the proton and the nucleus at higher x are important goals of the RHIC experiments discussed below.

Hard Scattering—Probing the Structure of Matter

At its most fundamental level, strongly interacting matter consists of light, pointlike quarks and powerful gluon fields. For example, the proton is built from two up quarks, a down quark, and an infinite number of quark-antiquark pairs and gluons. The theory of the interactions among these "partons" is called quantum chromodynamics (QCD). The partons interact by exchanging gluons, and the masses of the proton and the neutron are due mainly to the gluon fields. A nucleon (a proton or a neutron) might therefore be visualized as shown at right—a seething ensemble of a large and ever-changing number of constituents. Atomic nuclei, being largely composed of protons and neutrons, are likewise bound systems of quarks and gluons. A major aim of nuclear experiments through the next decade will be to take more detailed "snapshots" of this structure at various levels of resolution.

The fundamental quark and gluon structure of strongly interacting matter is studied primarily by experiments that emphasize hard scattering from the quarks and gluons at sufficiently high energies. Two important ways of probing the distribution of quarks and antiquarks inside nucleons are shown on the facing page.

In the first, an electron (or a muon, a heavier cousin of the electron) scatters from a single quark (or antiquark) and transfers a large fraction of its energy and momentum to the quark via a photon (shown as a squiggly line). Such deep inelastic scattering measurements carried out with high-energy beams have been the primary source of experimental information on the quark and gluon structure of matter.



Inside the nucleon. Within the theory of QCD, the nucleon has a complex internal structure, consisting of three valence quarks (large dots), which are continually interacting by the exchange of gluons (depicted as springs in this schematic picture). In contrast to the photons that are exchanged between electric charges, gluons interact not only with the valence quarks, but also with each other, creating and destroying gluons and quark-antiquark pairs (small dots).

Information on the quark and gluon distributions of the other hadrons, such as the pion and the kaon, is limited. Since many theoretical techniques have been able to make much more progress on the structure of the mesons than the baryons, measurements of the quark and gluon distributions of these short-lived objects, though difficult, are important and promise to provide considerable new insight into hadron structure. An electron-proton collider would determine the quark structure of mesons with high precision over a large kinematic range.

Because of their connection to the quantum numbers of the hadron and their role in understanding the spectroscopy of hadronic systems, the valence quark distributions have received considerable scrutiny—and yet they still pose significant puzzles. In rare situations, all of the momentum is carried by just one quark (the $x \rightarrow 1$ region). Understanding the way that the nucleon's momentum and spin are shared among the flavors of quark as this extreme is approached can provide vital information about quark and gluon dynamics. Since the measurements generally require nuclear targets, their interpretation needs precise understanding of the many-body effects that can change the quark and gluon distributions in a nucleus from those of a free proton and neutron. This is a central nuclear physics problem in its own right. New experiments with the upgraded 12-GeV CEBAF and with other flavor-sensitive probes have been proposed to accurately determine the flavor and spin dependence of the quark distributions as the quark carries an ever-greater fraction of the proton's momentum. If the predictions of QCD are not realized, most of the current theory of the valence structure of hadrons will need to be reevaluated.

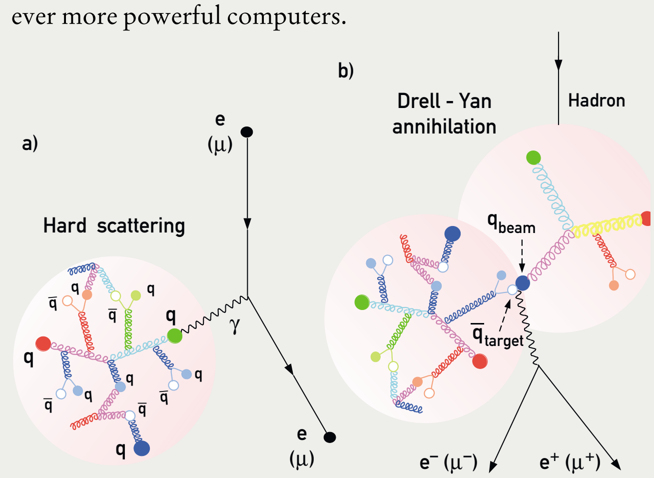
The electron (or muon) exquisitely probes the quark substructure of the proton with a known spatial resolution.

In a second kind of scattering, the Drell-Yan process, the antiquarks present in the target nucleon are probed more directly when a quark inside an incident hadron (a proton, say) has enough energy to annihilate with one of the antiquarks. The energy released by annihilation produces a "virtual" photon, which then materializes as an electron-positron or muon-antimuon pair at very high relative energy. Other proton-proton scattering reactions at high energy have the potential to provide new vistas on the quark and gluon structure of the proton, with sensitivities that are difficult to obtain with electron beams.

A central thrust of nuclear physics is to understand the structure of strongly interacting matter in terms of the fundamental quarks and gluons. Important questions being studied include:

- How do the proton's and neutron's various constituents contribute to its overall spin?
- How exactly are the protons and neutrons made from the different types of quarks?
- What role do quarks and gluons play in the structure of atomic nuclei? Are they important to understanding nuclear binding?

Essential to new insight are the recent advances in our theoretical understanding of hard scattering. In the last several years, an entirely new class of observables, called generalized parton distributions, has been identified by theorists. Further, it appears that at some scale the gluon density of strongly interacting matter must saturate. Where does this saturation occur and what are its properties? These insights have stimulated great interest and offer new approaches in the quest to understand nuclear matter. At a theoretical level, substantial progress continues to be made toward complete QCD calculations of nucleon properties, using ever more powerful computers.



Probing for quarks. The quarks and antiquarks inside a nucleon can be conveniently probed in two ways: (a) by deep inelastic scattering, in which an electron (e) or muon (μ) beam probes the substructure of the nucleon; or (b) by the Drell-Yan process, in which the probe is a beam of hadrons and where lepton-antilepton pairs are produced by quark-antiquark annihilation.

It is also informative to study the properties and behavior of hadrons in nuclear matter. For example, structural changes can occur in a very fast hadron as it passes through nuclear matter. This offers an opportunity to test QCD. During a hadron's short traversal time, quantum mechanics allows such a particle to fluctuate into states that are much smaller in size than the states that normally appear in free space. Therefore, as this "mini" hadron passes through a nucleus, it interacts more weakly with its neighbors than would a "normal" hadron, making the nucleus appear to be more transparent; this QCD effect is known as "color transparency." Recent data from Fermilab and from the HERMES experiment at DESY on the production of ρ mesons have confirmed both the presence of these small-sized components and the general concepts of color transparency. Understanding and studying the effect of this phenomenon is intimately related to understanding the origin of the *NN* interaction at very short distances. Electron-scattering experiments with beam energies substantially higher than those now available at CEBAF will be required to fully explore the implications of color transparency.

Spectroscopic information on the structure of hadrons relies on information obtained from much less violent collisions than those characteristic of hard scattering. A challenge is to understand how the behavior of quarks and gluons in the asymptotically free regime, as revealed by violent collisions, relates to the behavior at more modest energy scales, where the QCD forces become strong. Recent Jefferson Lab experiments on the excitation of resonances, which are due to the strong collective interactions among the quarks and gluons, show tantalizing similarities to the highly inelastic data where the constituents are almost free. This "duality" property may allow a connection to be developed between the fundamental quark-gluon degrees of freedom in QCD and more long-standing hadronic pictures.

At the other extreme of very small x values, the conditions are very different. Although individual quarks and gluons are almost free, their densities are extremely high, and interactions among them can become important. The first evidence of this shows up in a reduction of their densities in nuclei, as compared with nucleons, at low x, a phenomenon referred to as shadowing. At even lower x values, these parton interactions are predicted to lead to a new feature of strongly interacting matter, the emergence of a colored gluon condensate. Nuclear targets with an assembly of closely packed nucleons provide a simple way to increase the effective quark and gluon densities even further. The search for these exciting new phenomena will require high-resolution experiments at a future very-high-energy, high-luminosity electron-nucleus collider.

Hard scattering and spin structure. How the quarks, antiquarks, and gluons conspire to yield the 1/2 unit of angular momentum known to correspond to the intrinsic spin of the nucleon is not well understood, and a vigorous program of polarized hard-scattering experiments has been carried out at SLAC, CERN, and DESY to study this problem. Figure 2.5 shows the world's data on the spin structure functions for the proton and the neutron, g_1^p and g_1^n, respectively. The relative strengths of the proton and neutron data agree with the prediction of Bjorken's sum rule, thereby verifying the QCD analysis techniques used. However, the fit to the individual strengths of proton and neutron imply that only about one-fourth of the nucleon's spin is due to quarks. This raises the question, Is the dominant contribu-

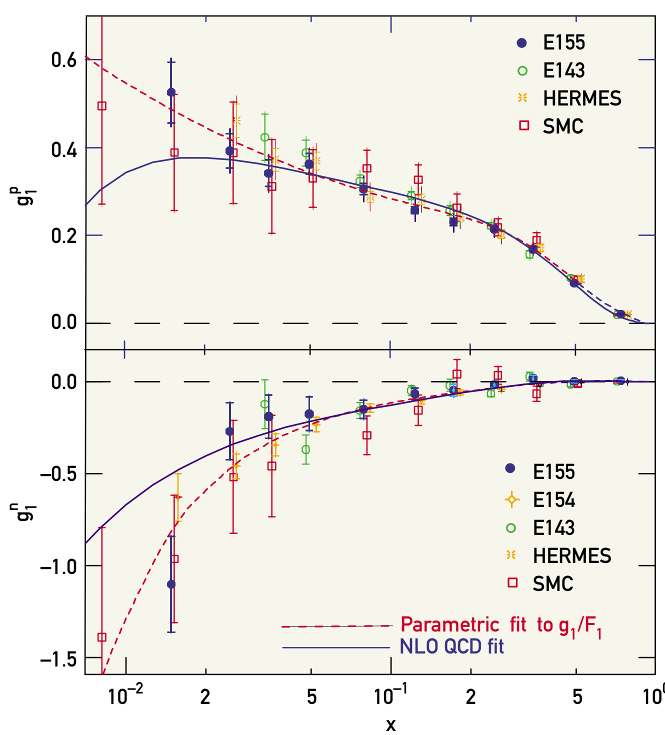


Figure 2.5. Momentum dependence of the spin structure functions for the proton and the neutron, g_1^p and g_1^n, respectively, evaluated at $Q^2 = 5$ (GeV/c)^2. The data are from experiment SLAC E155 (solid circles), E143 (open circles), and E154 (crosses); CERN SMC (squares); and DESY HERMES (stars). The solid curves correspond to a QCD fit that satisfies Bjorken's sum rule for the difference of the proton and neutron data, and confirm that the quarks carry only about one-fourth of the spin for either proton or neutron individually.

tion coming from gluons or perhaps from the orbital motion of the quarks? This is one of the most important open questions in hadronic physics.

The coming years afford an outstanding opportunity to tackle this question with three different experimental approaches, which are described in the following paragraphs:

- Direct measurements of gluon polarization
- Determination of the flavor structure of the quark polarization
- Transversity measurements

Experiments planned at CERN, SLAC, and RHIC aim to determine the gluon contribution to the proton's spin. At CERN the COMPASS experiment will employ beams of longitudinally polarized muons interacting with longitudinally polarized proton targets to probe gluon polarization. SLAC will study the photon-gluon fusion process with real photons. And at RHIC, where the proton beams can be polarized, quarks whose polarization is already known will be used to analyze the degree to which gluons are polarized within the proton via the quark-gluon Compton process. A comparison of the projected results is shown in Figure 2.6. When complete, these experiments will extend knowledge of the gluon polarization to momentum fractions as small as $x_{gluon} \sim 0.01$. Measurements of gluon polarization at still-lower momentum fractions (which are necessary to ensure that the total gluon contribution is precisely measured) will require a new collider of polarized electrons and polarized ions.

To obtain a full understanding of this problem, it will also be necessary to know how the spin is shared among the different quark and antiquark flavors over a wide range of x. Initial information about these flavor structures is available from semi-inclusive hard-scattering measurements, in which final-state hadrons are detected in coincidence with the scattered lepton. The recent HERMES run, with its ring-imaging Cerenkov detector that cleanly identifies the final-state hadrons, promises a more precise determination of the flavor structure of the quark and antiquark polarization. Additional information on flavor dependence will be forthcoming from RHIC, including measurements of the Drell-Yan process, production of electroweak bosons ($W^{\pm}$), and measurements of parity-violating asymmetries in collisions between longitudinally polarized proton beams.

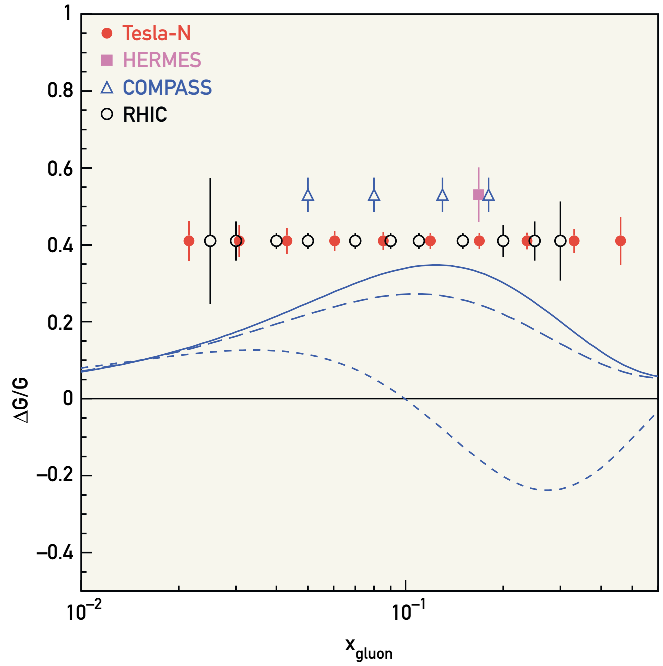


Figure 2.6. Future data on gluon polarization. Comparison of the anticipated precision and *x* range for data on gluon polarization from planned experiments (TESLA-N is still under consideration). Three different models of gluon polarization, all consistent with the existing polarized deep inelastic scattering data, are also shown.

Further insights into the enigma of the nucleon's spin will come from measurements of the so-called transversity structure function, which encodes the quark and antiquark polarizations in a transversely polarized proton. Comparing the transversity and net helicity distributions will expose one aspect of the degree to which relativistic effects are important in the quark structure of the nucleon. Preliminary results from the HERMES collaboration are intriguing, and further measurements are planned at HERMES, RHIC, and e^+e^- colliders.

QCD in the Confinement Regime

In the early 1970s, the spectrum of mesons and baryons led to the proposal that the quarks inside these particles are effectively tied together by strings. Today, the string theories that emerged from this idea are being examined as candidates for the ultimate theory of nature. While the strong interactions are described by QCD, which is not fundamentally a string theory, numerical simulations of QCD (lattice QCD) have demonstrated that this early conjecture was essentially correct: In chromodynamics, a stringlike chro-

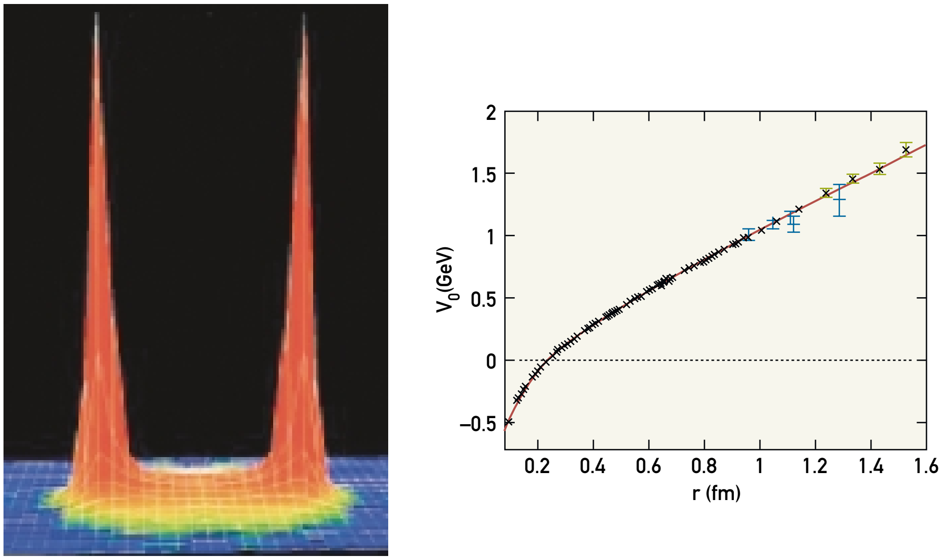


Figure 2.7. Fields of color. Lattice QCD has confirmed the existence of flux tubes between distant, static massive charges (left). The constant-thickness flux tube between the two quarks leads to a potential that rises linearly as a function of separation (right).

moelectric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see Figure 2.7). The phenomenon of confinement is the most novel and spectacular prediction of QCD—and unique among the known forces of nature. It is also the basic feature of QCD that drives all of nuclear physics, from the masses of the proton and other nuclear building blocks to the *NN* interaction.

An ideal experimental investigation of the confinement mechanism would be to fix a quark and an antiquark several femtometers apart and then to directly examine the flux tube that forms between them. One of the fingerprints of the gluonic flux tube would be its model-independent spectrum, its first excitation consisting of two degenerate states. These would be the longest-wavelength vibrational modes of this system and would have an excitation energy of π/r, since both the mass and the tension of this relativistic string arise from the energy stored in its color force fields. In reality, experiments must be based on systems in which the quarks move. Fortunately, both general principles and lattice QCD indicate that approximations to this dynamical model work quite well, at least down to quark masses of the order of 1 GeV.

To extend this understanding to yet-lighter quarks, models are required, but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV, a new form of hadronic matter must exist in which the gluonic degree of freedom of a quark-antiquark system (a meson) is excited. The "smoking gun" characteristic of these new states is that the vibrational quantum numbers of the gluonic string, when added to those of the quarks, give correlations among the spin, parity, and charge-conjugation quantum numbers that are not allowed for ordinary $q\bar{q}$ states. These unusual correlations are called exotic, and the states are referred to as exotic hybrid mesons. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations predict that these states exist in this mass region. These calculations demonstrate that the levels and their orderings will provide important information on the mechanism that produces the flux tube.

There is a great opportunity to address these important questions experimentally. Tantalizing evidence has appeared over the past several years, both for exotic hybrids and for gluonic excitations with no quarks (glueballs). For example, evidence is now available for two states with exotic quantum numbers and masses of 1.4 and 1.6 GeV. Both states have been confirmed by at least one other experiment. Intriguingly, the masses are lower than those expected from current predictions. In addition, observation of a scalar state at 1.5 GeV and the careful mapping out of its decays by the Crystal Barrel experiment at CERN indicate that the lowest-mass glueball and the normal scalar mesons are mixed. The field has reached a point where gluonic degrees of freedom are evident, but a program of spectroscopy to map out many of these states is needed to complete our understanding of the confinement mechanism.

Photon beams are expected to be particularly favorable for carrying out this spectroscopy program, because they lead to enhanced production of the exotic hybrids, compared with pion, kaon, or proton beams. To date, most meson spectroscopy has been done with these latter probes, so it is not surprising that the experimental evidence for flux tube excitation is tentative at best.

High-flux photon beams of sufficient quality and energy will be become available at Jefferson Lab when the facility is upgraded to 12 GeV. This project will accumulate statistics during its first year that will exceed existing photoproduction data by at least a factor of ten thousand and data with pions by at least a factor of a hundred. With the planned detector, high statistics, and linearly polarized photons, it will be possible to map out the spectrum of these gluonic excitations.

Theoretical input, particularly from the lattice, will also be needed to compare with the observed spectrum of states and eventually their decay patterns. Recent improvements in calculational techniques, coupled with the current lattice initiatives to build a new generation of computers, will make definitive calculations possible in the not-so-distant future. When the spectrum and decay modes of gluonic excitations have been mapped out experimentally, a giant step will have been taken toward understanding one of nature's most puzzling phenomena, quark confinement.

Yet another important issue in the physics of confinement is understanding the transition of the behavior of QCD from long distance scales (low Q^2, where confinement dominates and the interaction is very strong) to short distance scales (high Q^2, where the quarks act as if they were free). The pion is one of the simplest QCD systems available for study, and the measurement of its elastic form factor is the best hope for seeing this transition experimentally. Figure 2.8 shows how the proposed CEBAF 12-GeV Upgrade project can explore this transition.

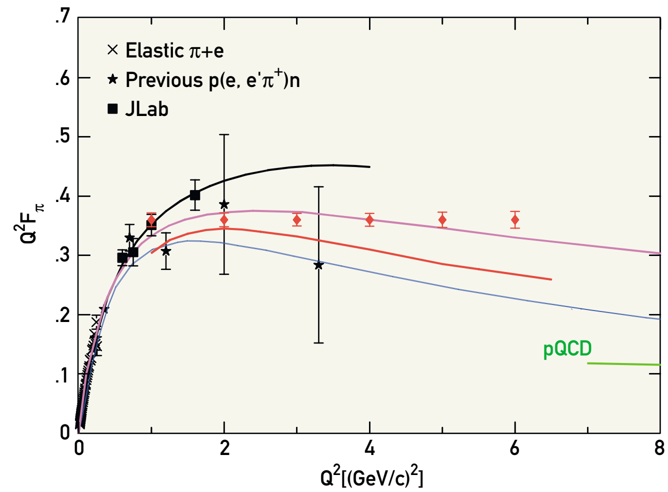


Figure 2.8. Projections for an upgraded CEBAF. The 12-GeV Upgrade will allow measurements of the pion elastic form factor through the expected transition region from confinement-dominated dynamics (at modest Q^2) to perturbative-dominated dynamics (at high Q^2). The colored symbols depict the expected precision at values of $Q^2 \leq 6$. The curves represent model predictions of this transition, while the pQCD result (lower right) is the predicted value at high Q^2.

The QCD Basis for the NN Interaction

At present, the best quantitative description of the force between two nucleons remains the phenomenological model of meson exchange. The long-range part of this *NN* force is mediated by pions, the lightest mesons. The short-range part is less well understood. While lattice QCD computational techniques are likely to provide detailed predictions of the properties of single nucleons, numerical solutions of QCD for systems of more than one nucleon are still tremendously challenging. However, in the next few years, lattice QCD will be able to provide qualitative insights into the interaction between two very massive hadrons (containing quarks more massive than *u* and *d*), which is a more soluble problem and involves the same mechanisms of quark interchange and gluon exchange that occur in the *NN* force.

Developing a deeper understanding of the origins of the effective *NN* force in terms of the fundamental constituents of QCD has recently become a realistic goal for nuclear physics through the use of effective field theories. These theories exploit the symmetries of QCD and enable its confrontation with low-energy observables. Combined with the computational techniques of lattice QCD, these methods have the potential to provide a powerful quantitative tool to connect QCD directly to the low-energy properties of nuclei.

Understanding the *NN* interaction is vital not only for gaining a clear picture of nuclear structure under normal conditions, but also for making reliable predictions for more extreme processes, such as those that take place in supernovae or when a hot, dense quark-gluon plasma condenses into nucleons and mesons. Effective field theories are now very successful in describing processes involving two nucleons at low energy, for example, *n*-*p* capture and the breakup of a deuteron by neutrino bombardment. The former process is central to predicting the abundances of elements from Big Bang nucleosynthesis, and the latter is required input to understand the flux of neutrinos from the sun. Work is currently under way on applying effective field theories to three-body processes and extending them to interactions among many nucleons.

Unique information on the strong force between hadrons can be obtained by comparing the force between two nucleons to that between a nucleon and a lambda particle, in which one of the quarks is a heavier strange quark. What is known of the ΛN force comes principally from the study of nuclei that contain one Λ, generated, for example, from reactions using K and π beams at Brookhaven's AGS. New instrumentation and experimental techniques have dramatically improved this field's capabilities. Arrays of high-resolution detectors of gamma rays at the AGS and electroproduction experiments at Jefferson Lab with greatly improved resolution will allow a detailed study of the spin and orbital angular momentum terms of the ΛN force. It is this component of the NN force that is responsible for the dominant characteristics of the shell structure observed in nuclei.

At the quark level, similar arguments can be made for the production of strange (and charm) quark-antiquark pairs with photon and electron beams. For example, in threshold production of the ψ meson, which consists of a charm quark-antiquark pair, the small $c\bar{c}$ state could have a residual color van der Waals–type interaction with a nucleon. Such a force is possibly a strong component of the NN force and could be studied by a search for ψ-N bound states or, equivalently, ϕ-N bound states with strange quark-antiquark pairs.

When two nucleons are separated by subfemtometer distances, their internal quark-gluon structures overlap, and a description in terms of QCD is expected to be necessary. Electron scattering from light nuclei is ideal for probing such microscopic aspects of nuclear structure. The essentially structureless electron, possessing both a charge and a magnetic moment, provides a direct and highly precise map of the charge and magnetization of nuclei; the momentum transferred by the electron governs the spatial resolution with which one can measure the distributions. The fact that electrons can be easily polarized is critically important, since the ground states of most light nuclei have nonzero spin. Polarized beams and the detection of polarized reaction products provide a necessary handle to separate the various contributions to the charge and magnetization.

The deuteron, with just one neutron and one proton, provides an excellent example of a light nucleus for such experiments. When the deuteron is polarized in one of its three possible quantum states, the spin 0 state, it has a toroidal shape; in the other two states (spin ±1), it appears to be a dumbbell. Such shapes are formed by the joint action of the short-range repulsive force and the anisotropic pion-exchange force between the nucleons. Disentangling the deuteron's electric charge distribution from its quadrupole moment requires a combination of two measurements of unpolarized electron scattering, along with a third, such as the deuteron's degree of alignment in the spin 0 state along its recoil direction, referred to as t_{20}.

New measurements of t_{20} from CEBAF are consistent with the meson-nucleon view of the NN force, even at distances of about 0.5 fm, where the internal structures of the neutron and proton overlap significantly. The average separation between the nucleons in the deuteron is about 4.2 fm; however, the deuteron density peaks at an internucleon distance of about 1 fm, where the nuclear forces are most attractive. Figure 2.9 shows the data compared with various meson-exchange models. At even higher momentum transfers, corresponding to even smaller distance scales, unpolar-

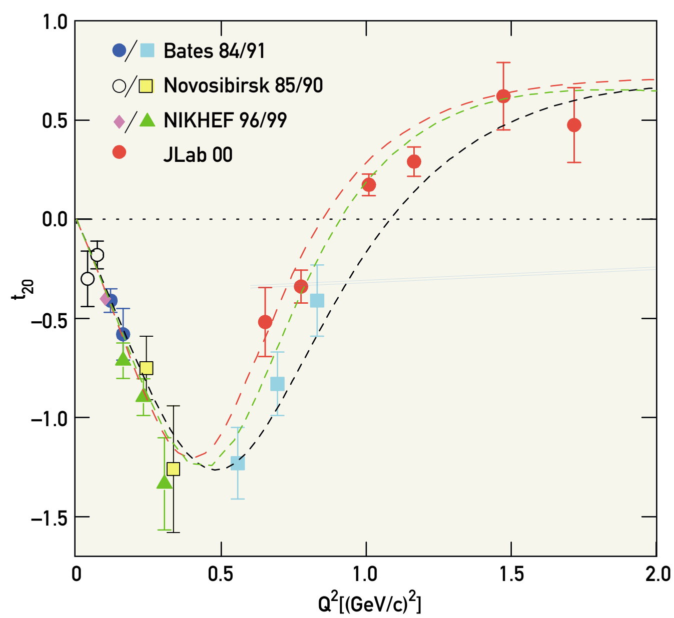


Figure 2.9. New t_{20} data from Jefferson Lab. Calculations using the traditional meson-exchange picture (the dashed curves) agree best with the new data, even at distance scales where the neutron and proton overlap significantly (at and above $Q^2 \sim 1$), whereas the perturbative QCD calculation (double solid line) does not describe the data at all.

ized data from CEBAF, shown in Figure 2.10, appear to be consistent with expectations from either the quark-gluon or the meson-nucleon view. To understand the range of applicability of the two pictures, it is essential to extend these and related measurements in deuterium and other light nuclei to the highest possible values of momentum transfer, where sensitivity to the quarks alone would be enhanced. Such a program can be carried out by upgrading the CEBAF accelerator to 12 GeV.

Another avenue for investigating the role of quarks in nuclei is by using high-energy gamma rays to break up the deuteron into a proton and a neutron. In general, the momentum transferred to the two nucleons can be substantially higher than in the case of electron scattering. It appears that high-energy two-nucleon breakup of deuterium is, in fact, consistent with the quark-gluon picture, whereas available meson-nucleon models fail to explain the data. Recent polarization data show very similar behavior, which would be completely unexpected in a meson-nucleon picture.

Even the best available model of the *NN* force cannot accurately explain nuclear binding. To reproduce the binding energies of the simplest light nuclei, it is necessary to add three-body forces to the pairwise interactions determined from nucleon-nucleon scattering (see "Theoretical Advances," pages 30–31). Unless such forces are considered, the binding energies of light nuclei are too small, and the binding of nuclear matter, relevant for understanding neutron stars, is too large. Precise new polarization data from the Indiana University Cyclotron Facility (IUCF) constrain the calculations of the spin-dependent part of the three-body force.

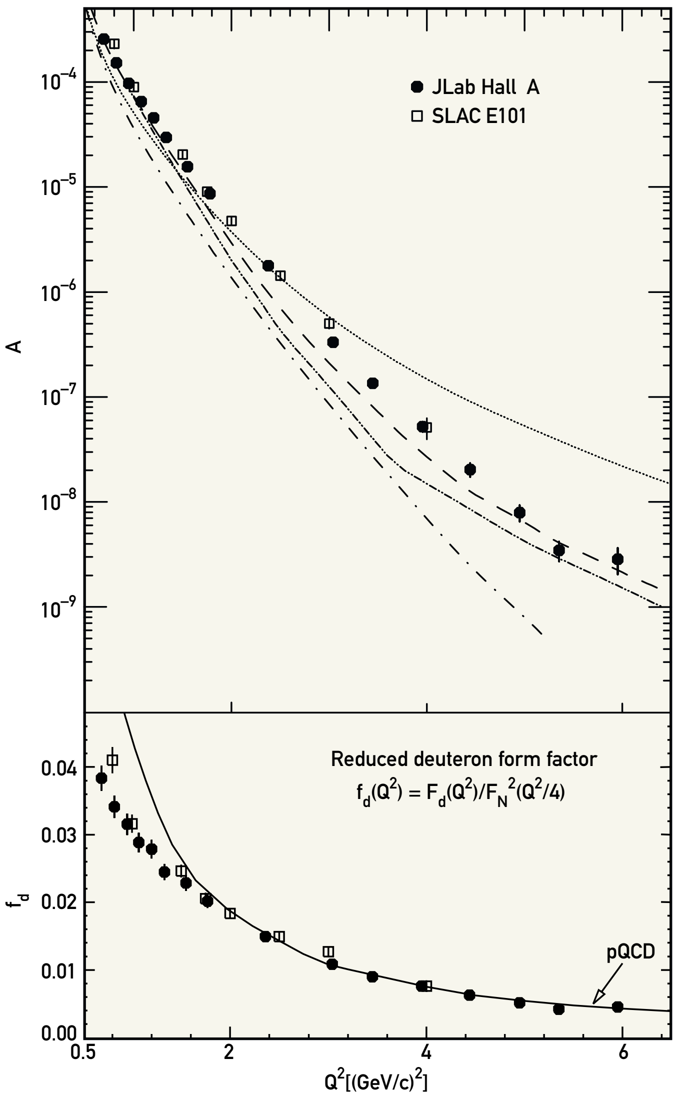


Figure 2.10. Electron-deuteron scattering results. Measurements of unpolarized electron-deuteron scattering cross sections from SLAC and Jefferson Lab, characterized by the structure function $A(Q^2)$, are consistent with meson-nucleon–based theories of nuclei (upper figure), while at higher Q^2, they also become consistent with the behavior predicted by quark-gluon–based theories (lower figure).

Theoretical Advances

In recent years, theoretical investigations of the internal structure of the nucleon, and hadrons in general, have focused mainly on achieving close ties to the fundamental theory of strong interactions, QCD. At present, three approaches are promising. The first is numerical simulation of lattice field theory, the only way known to directly solve "strong" QCD with controlled errors. A second approach focuses on low energies and exploits the spontaneous breaking of chiral symmetry that is an important consequence of strong QCD. This is the effective field theory approach (see above) that has been used with great success in establishing the Standard Model of electroweak and strong interactions. The third approach is perturbative QCD, a powerful tool to extract the structure of the nucleon from high-energy scattering processes.

Lattice QCD. Although the idea of lattice regularization was introduced shortly after the advent of QCD, only recently have the algorithmic, analytical, and computational tools been developed to the point that lattice QCD calculations can have a major impact. In particular, practical methods have been found for incorporating an exact form of chiral symmetry on a lattice, and all the tools are now at hand to undertake a large class of definitive lattice calculations of nucleon observables. Lattice studies also give invaluable insights into fundamental aspects of QCD. The lattice allows theorists to answer interesting questions inaccessible to experiment, such as how the properties of QCD change with the number of colors, quark flavors, or quark masses. New techniques under development may also enable study of the phases of dense hadronic matter and the transitions between them.

A wealth of experimental probes provides rich and precise measurements of the quark and gluon structure of the nucleon. The only way that the associated QCD matrix elements can be calculated directly is on the lattice. Examples of quantities that can be calculated include masses, form factors, quark-gluon distributions, and polarizabilities. Many calculations of nucleon properties have used lattices of moderate size, heavy quark masses, and "quenched" approximations (in which effects of the $q\bar{q}$ sea are truncated). These preliminary studies have provided algorithms and programs that can be used for realistic calculations, and the results obtained show qualitative agreement with experiment. Recent lattice results include calculations of (i) the nucleon electromagnetic form factors; (ii) moments of the spin-independent, helicity, and transversity distributions; (iii) the axial charges; and (iv) the contributions of strange quarks in the nucleon. It is important for the U.S. to invest in tera-scale computers in order to realize the exciting potential of lattice QCD.

Effective field theory. At long distances or low energies, where the interactions among quarks and gluons are strong, the mesons and nucleons become the useful degrees of freedom to describe the nucleon dynamics. This line of investigation can be justified in terms of effective field theories, which organize quantum field theories according to hierarchies of physical scales. An effective field theory is the most general description consistent with all underlying symmetries and physical principles, and it has the useful feature that the uncertainty associated with a calculation of any observable can be estimated and controlled. After spontaneous breaking of chiral symmetry, the relevant energy scales in QCD are the light quark (or Goldstone boson) masses and the momenta of the external probes. The effective field theory at these low-energy scales was first introduced over 30 years ago and is termed chiral perturbation theory.

This theory has enjoyed great success in describing the interactions with, and decay of, Goldstone bosons, such as pions, and its extension to include nucleons and other baryons has been investigated extensively. With nucleons, the convergence of the perturbative expansion is slower than in the case of the mesons. However, the theory leads to many predictions that can be compared with experiments, especially for Compton scattering (both real and virtual) and near-threshold pion photoproduction and electroproduction. The chiral expansion also allows calculation of quark mass contributions to polarized and unpolarized parton distributions, allowing the extrapolation of lattice calculations to the chiral limit.

Perturbative QCD. An exciting new area of study in perturbative QCD is deeply virtual Compton scattering, which can be used to measure "generalized parton distributions" (GPDs). The GPDs contain rich information about quark and gluon orbital motion and correlations in the nucleon. In the last few years, the GPDs and their connection to hard exclusive processes (hard scattering in which all of the reaction products are detected) have stimulated much theoretical and experimental activity. It now seems within reach to rigorously map out complete nucleon wave functions at the amplitude level, rather than merely the probability distributions that can be inferred from experiments involving inclusive processes. Information about the fractions of the nucleon spin carried separately by quarks and gluons, and about their orbital angular momentum, can be obtained from combinations of these observables.

The GPDs can be probed in a new class of hard exclusive processes. The simplest example is deeply virtual Compton scattering, in which leptons scatter inelastically from a nucleon target, producing a high-energy real photon, in addition to the recoiling nucleon. The cross section can be expressed as a convolution of calculable coefficients (characterizing the hard interaction between the electron and the quark) and GPDs, which describe the nucleon's structure. Other examples of hard exclusive processes are similar to these deeply virtual Compton processes, with a meson replacing the real photon, thus making it possible to extract information on meson structure from the experiment. A number of experiments, including those at Jefferson Lab, HERMES at DESY, and COMPASS at CERN, are vigorously pursuing this new area. The new window on nucleon structure that will be opened by the study of hard exclusive processes is one of the main physics motivations for such proposed facilities as the CEBAF upgrade, ELFE (European Lab for Electrons) in Europe, and an electron-ion collider in the U.S.

Outlook

Recent and planned experimental programs are expanding our understanding of the structure of the hadrons, the origins of confinement, and the QCD basis for the *NN* interaction. These studies must be carried out over a broad range of energy and distance scales in order to follow QCD from the partonic regime characteristic of hard scattering to the distance scales seen in finite nuclei.

In the short term, the highest priority for this subfield is to exploit the opportunities available at Jefferson Lab and with the RHIC spin program. Both of these programs are poised to make substantial advances, which are threatened by limited resources to operate the accelerator facilities. The *Facilities Initiative,* which has the highest priority in this long-range plan, is a key component in achieving the goals of the community. In the medium term, many of the outstanding scientific opportunities that have been identified in this chapter 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.

Almost every aspect of this subfield is connected in some way to QCD. The experiments currently under way or planned are unlikely to lead to breakthroughs in our understanding of this connection without comparable efforts on the theoretical front through the development of state-of-the-art techniques such as lattice QCD and effective field theories. These theoretical advances depend in turn on the major new computational facilities put forward in the *Large-Scale Computing Initiative.*

We have seen substantial progress in the past decade, and experimental and theoretical tools now in place or planned promise an exciting and enlightening future as we pursue the quest to understand the nature of strongly interacting matter in terms of the fundamental building blocks of QCD.

Atomic Nuclei:

Structure and Stability

Overview: Getting to the Heart of the Matter

The atomic nucleus is at the heart of all matter. Lying at the core of every atom and comprising over 99% of its mass, the nucleus is a unique many-body quantal system in which protons and neutrons interact via strong, electromagnetic, and weak forces. The desire to comprehend the world around us, from the smallest constituents of matter to the largest structures in the universe—and to achieve a degree of control over our surroundings—motivates much of basic science. It is natural, then, to seek to understand the inner workings of the nucleus, a crucial component of the natural world. Delineating its many properties and achieving a quantitative description of this fascinating system is the goal of nuclear structure research.

Over the past decades, we have learned much about the atomic nucleus, yet crucial questions remain:

- What are the limits of nuclear existence? Experiments have established which combinations of protons and neutrons can form a nucleus only for the first eight elements, and little is known about where the limits of stability lie for the heaviest nuclei. We do not understand key facets of the mechanism responsible for nuclear binding, and theoretical predictions of the limits of stability are particularly challenging, since they require very accurate solutions of the many-body quantum problem of strongly interacting particles.

- How do weak binding and extreme proton-to-neutron asymmetries affect nuclear properties? Virtually nothing is known about how protons and neutrons arrange themselves in neutron-rich nuclei, except for the lightest nuclei—and even there, surprises abound. There is a pressing need to understand the dramatic differences between the properties of stable and short-lived nuclei, especially in light of the fact that the latter play a major role in the origin of the elements and in shaping the reactions that occur in supernovae, some of the most cataclysmic events in the cosmos.

- How do the properties of nuclei evolve with changes in proton and neutron number, excitation energy, and angular momentum? By varying these physical quantities in a controlled manner, we have found that the structure of nuclei changes significantly, especially under extreme conditions. So far, little is known in this area, but progress is such that a unified microscopic description of all nuclei now appears to be less an aspiration than a realistic goal.

We will begin to address these questions at existing facilities in the next decade, but their ultimate answers will require the full power of the proposed Rare Isotope Accelerator (RIA). An important additional issue, which relies on the answers to all the questions above, is the ability to apply the findings of nuclear science to problems important to society. When the need arises, we must be able to know or predict the properties of nuclei relevant to biology, medicine, energy generation, and national security.

Studying the detailed properties of atomic nuclei is a challenging task that tests the ability of theoreticians to describe finite quantum objects and to understand how relatively simple structures evolve out of the complex interactions among their constituents. To achieve a quantitative understanding of the nature of nucleonic matter, the structure of nuclei must be explored; phases and excitation modes of nuclei resulting from the interactions between nucleons must be probed; and the dependence of these properties on proton and neutron numbers, excitation energy, angular momentum, and density must be examined. Some of the diverse and often complex phenomena that have been observed can be related to the motion of a few nucleons in a potential generated by the other constituents, while other properties are associated with the motion of the nucleus as a whole, such as rotations or various classes of oscillations. An essential part of our quest revolves around understanding these collective and single-particle aspects—and how they are interrelated—so that a single, microscopic description can emerge.

The study of nuclear structure has a direct impact on other aspects of nuclear science, including nuclear astrophysics and the physics of fundamental interactions. Atomic nuclei have proved to be unique laboratories for exquisitely precise tests of the descriptions of weak interactions and other fundamental laws of nature. There are also strong connections with other mesoscopic systems in atomic and condensed-matter physics. For example, the evolution of nuclear properties with increasing excitation energy provides a fascinating quantum analog to the general problem of transitions from ordered to chaotic motion. Very neutron-rich nuclei, far from the common isotopes found in nature, open the door to investigations of the often-unusual properties of weakly bound quantum systems. For instance, such nuclei can include regions characterized by entirely new forms of low-density, spatially extended, nearly pure neutron matter akin to that on the surfaces of neutron stars.

Recent advances in understanding the nucleus. Major conceptual and technical advances have revolutionized the study of nuclear structure over the past ten years, and nuclear structure studies have flourished with measurements and calculations aimed at nuclei both near and far from the valley of stability. Recent significant advances in several areas can be briefly summarized:

- Shell structure in exotic nuclei. Investigations of nuclear shell structure far from stability are fundamental to our understanding of nuclei and their synthesis within the cosmos. Recent landmark experiments include the observation of the doubly-magic unstable nuclei ^{48}Ni ($Z = 28$, $N = 20$) and ^{78}Ni ($Z = 28$, $N = 50$). In lighter neutron-rich nuclei, spectroscopic studies have demonstrated clear evidence for a reordering of nucleonic shells; for a weakening of the familiar shell closures around $N = 8$, 20, and 28; and for the emergence of a new shell gap at $N = 16$ in the most neutron-rich nuclei. These studies provide the first indications that our models of nuclear structure, developed near beta stability, are not adequate for nuclei with large neutron excesses. In the most proton-rich nuclei, where, counterintuitively, a strong Coulomb force inhibits charged-particle emission, proton decay has rapidly evolved from an exotic phenomenon to a powerful spectroscopic tool. First signatures of a new form of pairing have been seen in nuclei with equal numbers of protons and neutrons, and a new decay mode, nonsequential two-proton radioactivity, has been discovered.

- Collective excitations. We gain insight into the properties of nuclei by establishing and studying their basic modes of excitation. Recent advances include the discovery of the first candidates for the new collective modes of chiral rotation and wobbling motion in triaxial nuclei. Dynamical symmetries of the nuclear Hamiltonian have been explored, and the properties of nuclei with very elongated (superdeformed) shapes have been elucidated. In particular, light superdeformed nuclei have been discovered. They provide a unique opportunity to study the underlying microscopic structure of collective rotations. Definitive excitation energies and quantum numbers have been determined for the first time in the key superdeformed nuclei ^{152}Dy and ^{194}Hg.

- Synthesis, structure, and chemistry of the heaviest elements. The discovery and investigation of the heaviest nuclei test our understanding of which combinations of neutrons and protons can give rise to long-lived superheavy nuclei, and extends the periodic table, fundamental to all of chemistry. Significant achievements within the last several years include the synthesis of new superheavy elements; the first chemical studies of seaborgium ($Z = 106$), bohrium ($Z = 107$), and hassium ($Z = 108$); and the first in-beam gamma-ray spectroscopy of the transfermium nucleus nobelium ($Z = 102$).

- Nuclear structure theory. Enormous progress has been made in the microscopic description of nuclei, including ab initio calculations for light nuclei and advances in the shell model and mean-field theory to include improved effective interactions and coupling to the continuum for studies of weakly bound systems. These advances enabled theorists to make detailed quantitative predictions of structure and reaction aspects of nuclei.

Looking ahead: A concise roadmap. Current progress in understanding the properties of nuclei is impressive, and the field is poised for significant breakthroughs over the next decade. A deeper understanding of the atomic nucleus will be achieved by efforts in both nuclear structure theory and experiment, where each discipline takes its inspiration from the other. But the impetus in both areas lies increasingly with studies of nuclei under extreme conditions, especially those with extreme proton-to-neutron ratios. In the near and intermediate-term future, complementary studies both near and far from stability will be pursued at stable-beam accelerators, such as those at Argonne and Berkeley Lab and at a number of universities, as well as at existing dedicated exotic-beam facilities, especially HRIBF at Oak Ridge and the new projectile fragmentation facility of the NSCL at Michigan State. In the longer term, the properties of the new and currently inaccessible rare isotopes that inhabit the very boundaries of the nuclear landscape will be the focus of greatest interest—thus the high priority accorded the proposed construction of RIA, a bold new concept with tremendous discovery potential.

Nuclear Structure Theory

The nucleus is a remarkable quantal system displaying diverse and rare phenomena. Governed by the strong interactions among nucleons, nuclei exhibit correlations resulting in both single-particle and collective modes of excitation. Nuclear structure theory attempts to understand these excitations and the responses of nuclei to different external probes, within a coherent framework. This theoretical framework must encompass a wide range of energy and momentum scales for nuclei ranging from the deuteron to the superheavy elements. Theory strives to describe the structure and dynamics of these often-disparate systems and to apply the understanding thus achieved to unravel some of the mysteries of the universe. For more on recent advances, see "Theoretical Advances," at right.

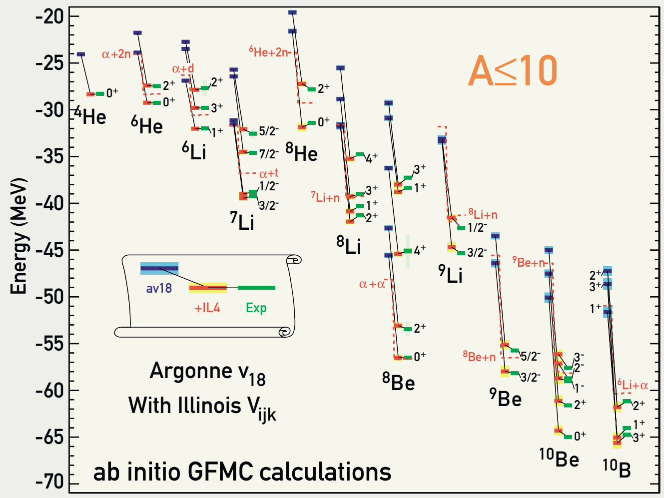
In recent years, much of nuclear theory has started from a traditional description of the nucleus as a system of interacting nucleons and associated currents. This starting point poses fundamental questions for the field: How does a so-called effective theory arise from such a traditional beginning as a reasonable approximation to quantum chromodynamics (QCD)? And what determines its range of validity? Techniques based on chiral symmetry have provided some answers to the first question, producing effective theories with dominant two-body interactions. Experiments at facilities such as Jefferson Lab are helping with the second question, testing the predictions of both traditional and QCD-based calculations over momentum ranges where the validity of neither is clear. A long-term objective is to develop a nonperturbative QCD technique, such as lattice QCD, that matches nucleonic descriptions at such an intermediate scale, thereby determining the low-energy parameters of nuclear interactions from QCD.

Within a framework that describes the nucleus in terms of interacting nucleons, research has taken several directions. The foundations of independent particle motion and the microscopic origin of nuclear shell structure continue to be explored, as are more recent issues concerning the impact of unbound states on weakly bound systems, the response of nuclei to external electroweak probes, and precise calcu-

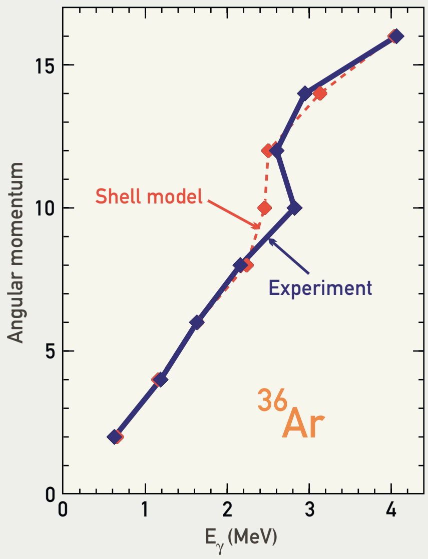
Theoretical Advances

Nuclear structure theory strives to develop "the" comprehensive model of the nucleus—a model that must encompass a wide range of energy and momentum scales, for nuclei ranging from the deuteron to the heaviest elements. Nuclear theorists try to understand bulk properties of nuclei and nuclear matter, nuclear excitations, and the response of nuclei to diverse external probes.

We have seen significant advances in microscopic modeling of nuclear structure in recent years, due in large part to recent increases in computational power and to associated algorithm developments. Indeed, access to national computing facilities remains an important ingredient in nuclear theory research. For the lightest nuclei, theorists can solve the equations describing the nucleus exactly. Here, the state of the art is the work on few-nucleon systems, based on the free nucleon-nucleon interaction, augmented by a three-body force. Such calculations, which are only possible on the best modern computers, allow us to predict the properties of nuclei with masses up to ten. The calculated and experimental spectra for nuclei with $A = 4$–10 are shown in the figure below. As these results show, even the best available parameterization of the pairwise interaction between nucleons cannot accurately explain nuclear binding. To reproduce the measured binding



Three-body forces at work. These energy-level diagrams for nuclei with $A = 4$–10 demonstrate the importance of including three-body forces in the calculation of nuclear binding. The results marked av18 excluded three-body forces, whereas those marked +IL4 included them. The latter show excellent agreement with experiment.



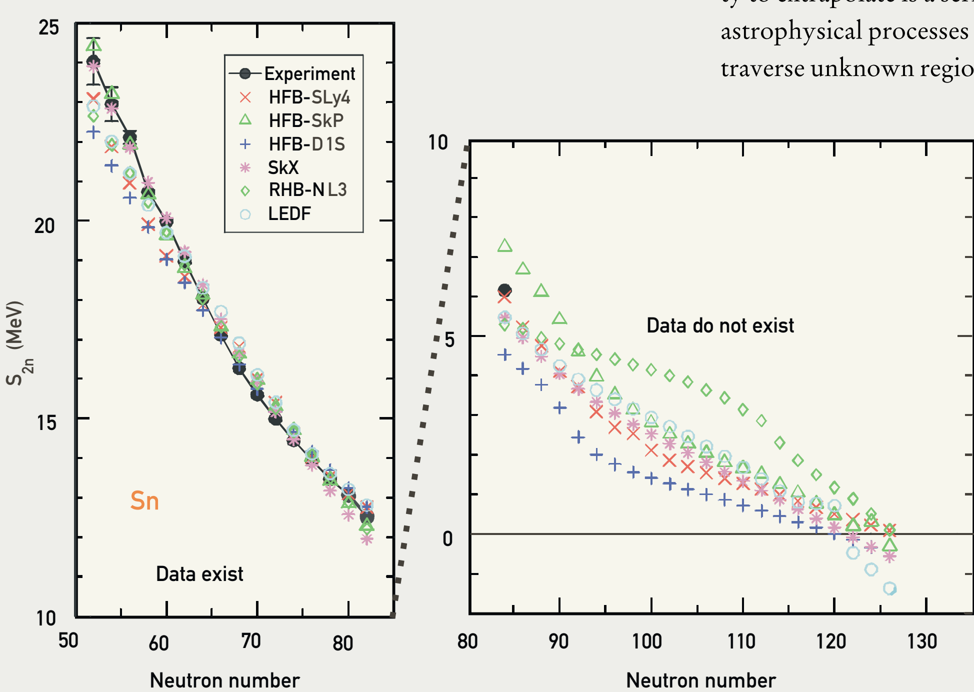
Triumph of the shell model. The plot shows the remarkable agreement between the experimental and calculated angular momenta in the superdeformed band of ^{36}Ar, as a function of the gamma-ray energy E_γ. The rotational frequency of the nucleus is simply equal to $E_\gamma/2$.

energies of the simplest light nuclei, it is essential to consider three-body forces. Such three-nucleon forces are expected because the nucleons are themselves composite objects. (A familiar example of a three-body force can be found in a system comprising the Earth, the moon, and an artificial satellite. The tides induced by the moon in the Earth's oceans alter the Earth's pull on the satellite.) The nuclear three-body forces are believed to be rather weak, and they have not yet been determined accurately.

For heavier nuclei, various methods based on the concept of nucleons moving in orbits, or shells, and interacting via pairwise effective forces have been very successful in predicting nuclear properties. A triumph of the nuclear shell model is the description of collective rotational states of medium-mass nuclei. Such calculations elucidate the origin of collective rotation in terms of the individual motion of protons and neutrons. The diagram at the left shows experimental and calculated results for ^{36}Ar. The calculations beautifully reproduce the collective rotation observed at low spins (where angular momentum increases linearly with gamma-ray energy), as well as the irregularity observed at higher rotational frequencies where nucleonic pairs break.

The figures below show the two-neutron separation energy (that is, the energy needed to remove a pair of neutrons from the nucleus) for the heavy even-even tin isotopes, as predicted using several microscopic models based on mean-field theory. The starting point for such calculations is the parameterization of the nuclear energy in terms of nucleonic densities. This theory is well known in other fields, such as quantum chemistry and condensed-matter physics. The calculations shown in the plot agree well—with one another and with the experimental data—in the region where experimental data are available, but they diverge (from one another) for neutron-rich isotopes with $N > 82$. Clearly, more experimental data for neutron-rich isotopes are needed to determine the density dependence of the effective interaction.

In addition to revealing our lack of a comprehensive nuclear model covering the entire nuclear chart, our inability to extrapolate is a serious problem in the context of astrophysical processes of nucleosynthesis, whose paths traverse unknown regions of the nuclear chart. The Rare Isotope Accelerator will provide the opportunity to address this issue by probing how key concepts of nuclear structure evolve with nucleon number.



The value of data. Calculated two-neutron separation energies for even-even isotopes of tin are shown here in the region where experimental values also exist and in the region ($N > 82$) where no such data are available. The calculations used several microscopic models based on mean-field theory.

lations of reaction rates at energies relevant for astrophysics. While essentially exact calculations are now possible for few-body systems, various approximations must be invoked in describing heavy nuclei because of their inherent complexity. The transition from one type of description to the other is also being explored. Whether a simple picture of effective interactions and operators will evolve, and what its crucial features will be, remain open issues.

The Hamiltonian required to describe the structure of nuclei is not known a priori. Accordingly, its accurate determination is a high priority, as is establishing and understanding the relationships among different approaches to nuclear many-body theory. We have seen major progress along several lines since the 1996 long-range plan. One such line involves the use of bare, nonrelativistic two- and three-nucleon interactions in the Schrödinger equation. Recent calculations have shown that nuclear structure indeed develops from the underlying nucleon-nucleon and three-nucleon forces, and that the properties of light nuclei can be reproduced satisfactorily. A second approach, focusing also on light nuclei, involves the use of effective field theory. This approach is based on the equivalence, at sufficiently low energies, of QCD and an effective theory, provided that the latter respects the underlying symmetries of QCD. During the last five years, significant progress has been made in studying the deuteron and three-body nuclei by this means. A third approach uses an effective Hamiltonian within a restricted model space. This effective interaction can, in principle, be derived from the bare interaction. Shell model techniques can then be applied to this effective Hamiltonian to calculate the structure of the nucleus of interest. Recently, with major computational advances, the nuclear shell model approach has been successfully applied to the description of moderately heavy nuclei ($A \sim 60$). Finally, self-consistent mean-field theories offer a fourth microscopic approach to nuclear structure. In this approach, the dependence of energy on nucleonic densities is defined, and an appropriate effective many-body Hamiltonian is solved for the ground state and bulk properties of a given nucleus, as well as for collective excitations.

Complementing these microscopic approaches, major advances continue to be made with models focusing more directly on the collective building blocks of nuclear structure. New collective modes, both in nuclei near stability and in those near the neutron drip line, have recently been discussed, new descriptions of shape-transitional regions have been developed, and new nuclear collective excitations have been proposed. Continued work on these more macroscopic models—often based on symmetry considerations—is called for, especially in regards to their link to the underlying forces at play in the nucleus. It still remains a major challenge for nuclear theory to understand these simple models, their ranges of applicability, and the underlying coupling schemes.

Collective degrees of freedom dominate many aspects of nuclear structure: Despite the complexity of the underlying quantum mechanics, nuclear responses often exhibit a simplicity associated with either single-particle modes or collective modes such as rotation and vibration. A number of question related to such modes thus remain at the forefront: What are the relevant degrees of freedom of the nuclear many-body system? What is the microscopic origin of collectivity? How does structure evolve with increasing nucleon number? Are there new collective modes in weakly bound systems? And what is the mechanism (or mechanisms) behind large-amplitude collective motion such as fission or shape coexistence?

Several important theoretical challenges must be faced during the next decade. The experimental emphasis on nuclei far from the valley of beta stability—nuclei to be investigated with RIA—requires further exploration of nuclear forces and currents, effective interactions, and techniques to solve the nuclear many-body problem in the regime of weak binding. This will provide the necessary tools to address questions concerning the mechanism of binding in exotic nuclei, the possible clustering in neutron skins, the role of correlations in low-density nuclear zones, and the description of soft, collective modes of excitation. Furthermore, many nuclear systems (including nuclear matter) that are important in astrophysical environments cannot be probed in the laboratory. Reliable theoretical tools must be developed to describe such systems accurately.

Exploring the Nuclear Landscape

Since the 1996 long-range plan, important new experimental results have added significantly to our understanding of nuclear structure. These advances are due, at least in part, to continuous improvements in the capabilities of accelerators and to successes in the quest for detection systems with

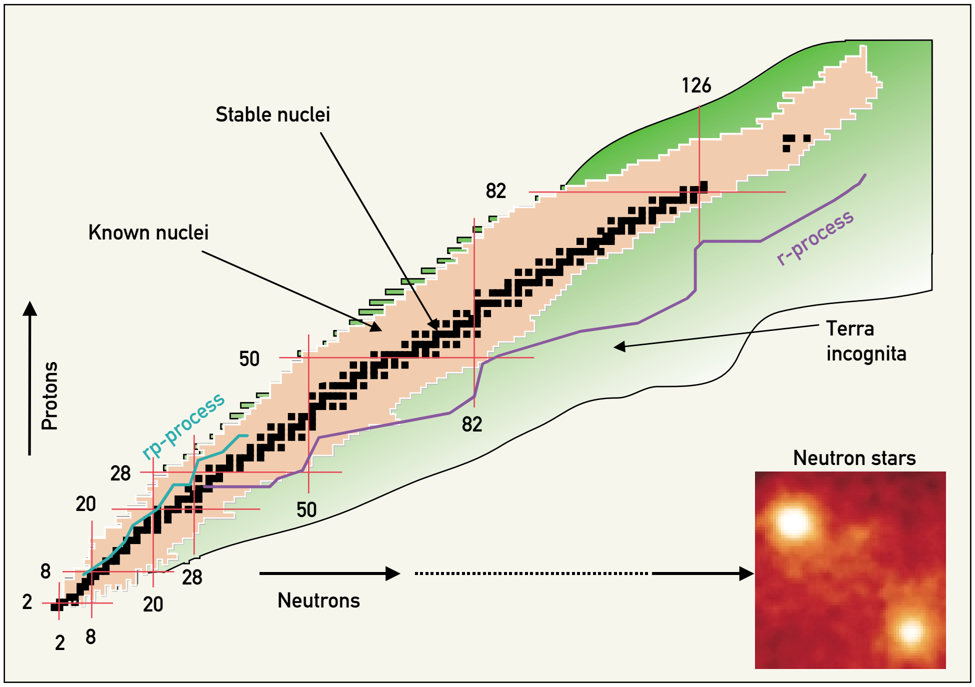


Figure 2.11. The nuclear landscape, defining the territory of nuclear physics research. On this chart of the nuclides, black squares represent stable nuclei and nuclei with half-lives comparable to or longer than the age of the Earth. These nuclei define the "valley of stability." By adding either protons or neutrons, one moves away from the valley of stability, finally reaching the drip lines where nuclear binding forces are no longer strong enough to hold these nuclei together. The dark yellow region shows the range of unstable nuclei that have been produced and studied in laboratories. But many thousands of radioactive nuclei with very small or very large *N/Z* ratios have yet to be explored. This nuclear terra incognita is indicated in green. The proton drip line is already relatively well delineated experimentally up to $Z = 83$. By contrast, the neutron drip line is considerably further from the valley of stability and harder to approach. Except for the lightest nuclei, the neutron drip line can only be estimated on the basis of nuclear models. The red vertical and horizontal lines show the "magic numbers," reflecting regions of high stability. The anticipated paths of astrophysical processes for nucleosynthesis (r-process, purple line; rp-process, turquoise line) are also shown. The Rare Isotope Accelerator (RIA) will enable studies of exotic radioactive nuclei far from the valley of stability, important for both nuclear structure studies and nuclear astrophysics.

increased sensitivity. These discoveries relate to nuclei dispersed over the entire nuclear chart (see Figure 2.11) and, as a result, the data shed new light on many facets of nuclear structure. The following sections expand on some of these discoveries and indicate how they point to the future.

Nuclei near stability: Collective modes and phase transitional behavior. Significant advances in understanding nuclei lying along the valley of stability include, among other insights, new information on vibrational modes and dynamical symmetries. Considering the fact that the frequency of nuclear vibrational motion is comparable to that of single-particle motion, the mere existence of collective vibrational states in nuclei is remarkable. The identification of multi-phonon states is then of importance, since their existence relates directly to this interplay of single-particle and collective degrees of freedom, and to the influence of the Pauli principle on collective modes. The search for such states has recently been successfully expanded to include vibrational modes with several phonons and with phonons of different multipolarities.

New experimental studies with samarium isotopes have shown that nuclei can exhibit behavior resembling that of phase transitions found in other many-body systems. These isotopes are transitional in that they are located on the nuclear chart between spherical and deformed nuclei; as a result, they display intense competition between different degrees of freedom (see "Nuclear Phases," pages 34–35). This work has inspired the development of analytic predictions for critical-point nuclei. Examples of such critical points have now been identified empirically, and further study of phase transitional behavior both near and far from stability is an exciting ongoing challenge.

Nuclear states at high angular momentum. With advanced gamma-ray detector arrays such as Gammasphere, we continue to make impressive progress in investigating the evolution of nuclear structure with increasing angular momentum and excitation energy. For example, high-spin states have now been studied for the first time in such important doubly-magic nuclei as ^{48}Ca, ^{132}Sn, and ^{208}Pb, identifying as a function of energy the dominant nucleonic excitations and collective modes.

Specific nucleons can play a dramatic role in driving the shape of the nucleus, as was illustrated recently by the discovery of very elongated (superdeformed or SD) shapes in ^{36}Ar and in the doubly-magic ^{40}Ca and ^{56}Ni. Such discoveries in light nuclei are especially important, since they provide the opportunity to study highly collective states in the framework of both nuclear shell model and mean-field approaches and, hence, to investigate the microscopic origin of collective rotation. Other achievements in the area of superdeformation relate to the discovery of new regions of SD nuclei near $A \sim 60$, $A \sim 90$, and $A \sim 110$, and to the first evidence for triaxial extended shapes near $A \sim 170$. Moreover, for the first time, we have determined the actual excitation energy and the specific quantum numbers (spins and parity) of a few SD bands in the well-established $A \sim 150$ and $A \sim 190$ regions. This was done by observing weak, one-step transitions linking the SD states with the "normal" levels that characterize the equilibrium shape of the nucleus.

These results provide severe tests for models calculating the impact of shell effects on the total energy. The fact that key residual interactions such as pairing are attenuated at high spin has emerged from studies demonstrating that a picture of extreme single-particle motion applies in this regime. This represents the best example thus far of the application of the shell model at extremes of angular momentum and deformation.

Nuclear Phases

Ordinary matter can undergo a change from one physical state to another, in response to changes in such variables as temperature or pressure. These changes are called phase transitions. Water, for example, under normal atmospheric pressure, undergoes abrupt phase transitions from solid (ice) to liquid to vapor as the temperature rises. Similar transitions can be induced by changing the pressure at a constant temperature. Beyond a certain point, however, uniquely defined by its temperature and pressure, the distinction between liquid water and water vapor is lost; this point is the "critical point." The location of the phase boundaries and the critical point represent two of the most fundamental characteristics of any substance.

Over the last few years, applications of the concept of phase transition have been extended, even to biological systems and to social, financial, and computer networks. In particular, phase transitions in small physical systems, such as atomic nuclei, metallic superconducting grains, metal clusters, quantum dots, and Bose-Einstein condensates, have attracted increasing attention.

In contrast to macroscopic ("infinite") systems, small systems such as clusters or nuclei manifest finite-size effects that may compromise the signatures of a phase transition. However, the strongest transitions can still survive, although they become muted and more gradual. Examples of observable phase transitional behavior in nuclei include the collapse of nuclear superconductivity with increasing temperature and/or angular momentum (the nuclear Meissner effect), shape transitions and shape coexistence phenomena, the liquid-gas transition expected to occur in heavy-ion reactions, and a number of transitions associated with the quark-gluon degrees of freedom.

Shape transitional phenomena are illustrated at the near right for the case of samarium. Here, the different "phases" are different nuclear shapes, which depend on the number of neutrons in the nucleus. Nuclei have been observed in both spherical and deformed phases, as well as in "critical-point" states.

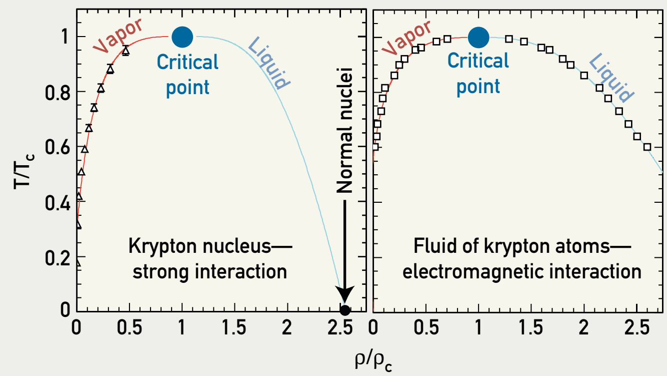
The second figure shows the results of a recent series of experiments that have characterized the liquid-to-vapor phase transition in nuclei. This represents the first time an experimentally derived phase diagram has ever been made for a system governed by the strong force acting inside nuclei, rather than by the electromagnetic force that governs the everyday matter in the world around us. Nonetheless, the similarity of the diagrams representing phase transitions in these two different regimes is striking, a reflection of the fact that the effective forces between nucleons (governed by

New forms of quantum rotation have been found in several regions of the nuclear chart. One involves a gradual closing with increasing angular momentum of the angle between the angular momentum vectors carried by the neutrons and protons (shears mechanism). Another concerns the possible existence of so-called chiral bands and is intimately related to the rotation of a triaxial body. Both of these new modes require that the protons and neutrons occupy specific states with high intrinsic angular momentum, and the description of these modes contributes to our understanding of correlations between protons and neutrons in nuclei.

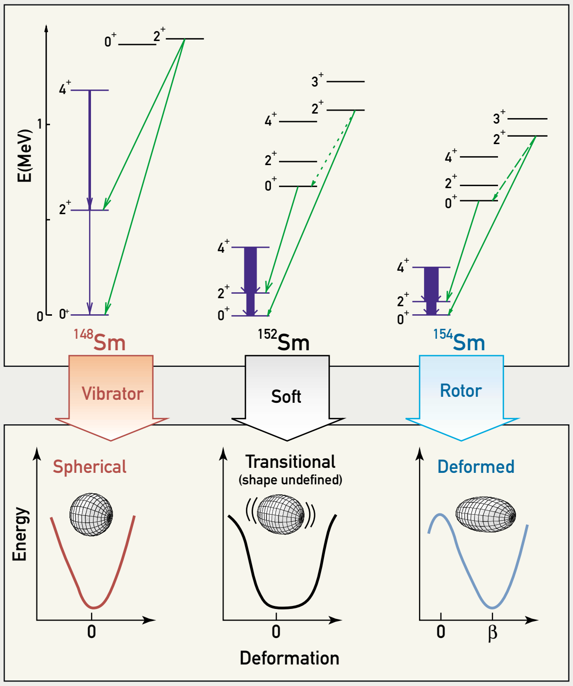
In the presence of large angular momentum, the intrinsic nucleonic density is strongly polarized; that is, the nucleus exhibits the variety of phenomena and behavior characteristic of condensed matter in a magnetic field: ferromagnetism, the Meissner effect, and the Josephson effect. The nuclear magnetism is caused by the spin-dependent parts of the effective interaction. Understanding the structure of these terms and the associated fields, which are dramatically amplified by the huge Coriolis interaction, is a major challenge for nuclear structure research. Such studies, requiring unparalleled resolution and selectivity, will certainly profit from the next generation of gamma-ray tracking arrays.

Such studies will then provide important benchmarks for the exploration of the exotic nuclei that are now within reach, first with the exotic-beam facilities that have just come on-line and, later, with RIA. For example, some of the properties of high-spin states provide information on cross-shell excitations that play a crucial role in exotic nuclei far from stability. Such properties also offer insight into the importance of pairing and other correlations in neutron-rich nuclei.

the strong force) are similar to those between molecules in many ordinary liquids (governed by the electromagnetic force). In both cases, the force is repulsive at short distances yet attractive at long distances. The critical temperatures and densities, however, are very different: For a collection of krypton atoms, $T_c = 209$ K and $\rho_c \cong 0.1$ moles cm^{-3}; for a collection of nucleons inside a krypton nucleus, $T_c \cong 8 \times 10^{10}$ K and $\rho_c \cong 8 \times 10^{13}$ moles cm^{-3}.



Liquids and gases. Experimental phase diagrams are shown here for the nucleus of a krypton atom (left) and a macroscopic fluid of krypton atoms (right). The vertical axis is temperature (as a fraction of the critical temperature T_c); density (as a fraction of the critical density ρ_c), rather than pressure, has been chosen for the horizontal axis.



Shapes of samarium. The energy-level schemes for three excited isotopes of samarium are shown at the top of the figure, and the inferred nuclear shapes are shown below. The isotope ^{148}Sm shows features characteristic of a spherical vibrator, whereas ^{154}Sm exhibits rotational bands typical of a deformed (elongated) nucleus. On the other hand, ^{152}Sm behaves like a critical-point system, whose shape cannot be precisely defined. This is illustrated in the energy diagrams below the shapes, where energy is plotted as a function of shape deformation. Well-defined minima exist for two of the isotopes, but the energy minimum for ^{152}Sm is very broad, and it is impossible to say whether the nucleus is spherical or deformed.

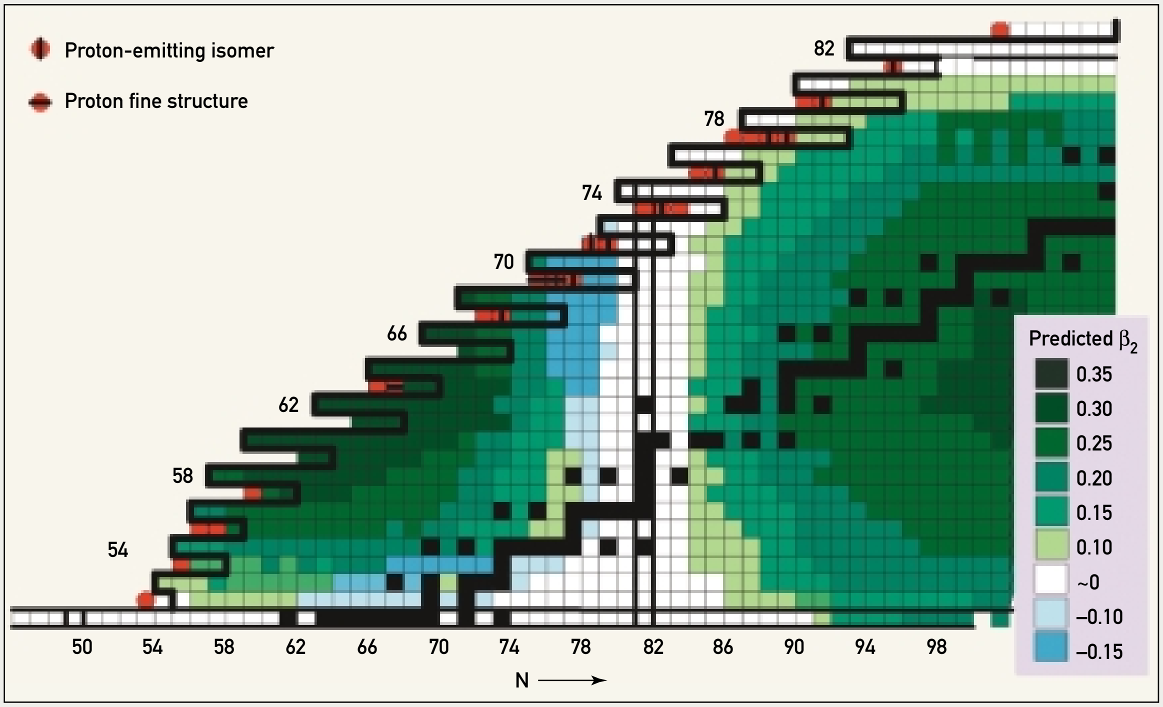
Beyond the Proton Drip Line

On the nuclear landscape (see Figure 2.11), the proton drip line is defined by the most massive bound nucleus of every isotonic (N = constant) chain. The calculated location of the proton drip line for nuclei with atomic numbers Z = 50 to Z = 82 is indicated by a thick black line in the figure shown below. For nuclei that lie above this line, the last proton has a positive energy and, hence, is unbound. This is not to say that such a proton escapes from the nucleus instantaneously! On its way to freedom, the proton must overcome a very wide energy barrier in the region where the attractive nuclear potential overwhelms the repulsive Coulomb force.

Escape is therefore forbidden in classical physics, but it occurs in the microscopic world of the nucleus as a result of quantum tunneling. The proton decay probability is sensitive to the energy and angular momentum of the proton, as well as to the properties of the nuclear states before and after decay. The important difference between proton emission and the well-known phenomenon of alpha decay lies in the fact that the latter process is influenced by the formation of an alpha particle inside the nucleus, whereas the proton is readily available for the decay process. Known proton emitters are indicated in red in the figure.

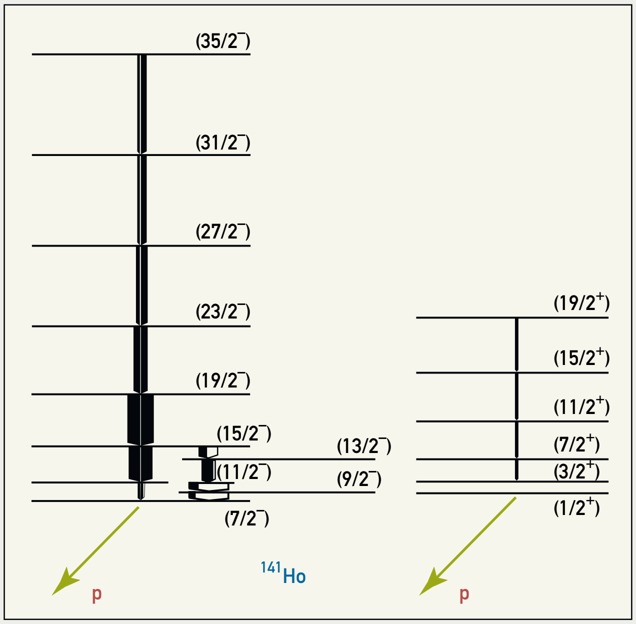
Proton emission has rapidly evolved from a newly observed phenomenon to a powerful tool providing information on basic nuclear properties. In situations where the decaying nucleus is deformed, quantum tunneling through a three-dimensional barrier takes place. The quadrupole deformation β_2 indicates the quadrupole shape deformation: A spherical shape corresponds to $\beta_2 = 0$, positive values describe "prolate" (football-shaped) nuclei, and negative values indicate "oblate" nuclei (flattened spheroids).

Experimental evidence that nuclear deformation needs to be considered has become available only recently, when measured half-lives in some nuclei could not be reproduced by calculations that assumed tunneling through a spherical barrier. The first cases reported were ^{141}Ho and ^{131}Eu. In the case of ^{141}Ho (Z = 67; see illustration at the upper right), where two proton-emitting states have been discovered, the presence of deformation has been confirmed by the observed sequences of nuclear states characteristic of the rotation of a deformed, prolate nucleus. Because the first excited state in deformed nuclei lies at a very low excitation energy—typically only a few hundred keV above the ground state—proton decay to such a level can compete with the usual decay to the

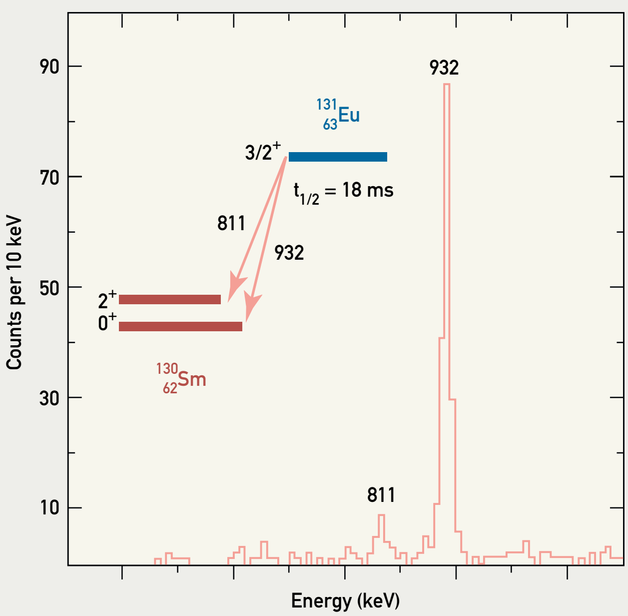


Life at the edge. This segment of the chart of nuclides shows the proton drip line (heavy black line) for atomic numbers 50 through 82. The red dots indicate systems for which proton decay has been observed; a horizontal line through the dot indicates the observation of fine structure. The parameter β_2 indicates the degree of deformation for the ground state of each nucleus.

ground state. This is referred to as fine structure in proton decay and has been observed in a few cases, for example, in ^{131}Eu ($Z = 63$), for which the data are shown in the lower figure below.



Rotating proton emitters. The band structures seen on top of the two proton-emitting states of ^{141}Ho are associated with the rotation of this nucleus. Their presence confirms the sizable deformation of ^{141}Ho that had been inferred originally from the measured proton-decay half-lives.



Fine structure in europium. In ^{131}Eu proton decay has been observed to both the ground state of ^{130}Sm and to the first excited state of the deformed nucleus, as shown by the small spectral peak observed at 811 keV.

The proton drip line and beyond. Properties of nuclei at or near the proton drip line address a number of fundamental questions. First, establishing the exact location of the drip line represents a stringent test for mass models and constrains the path of nucleosynthesis (rp-process). In addition, because of the stability provided by the Coulomb barrier, it is possible to study quasi-bound states in nuclei that actually lie beyond those that would be bound by the strong force alone. Such nuclei eventually decay, via quantum tunneling through a three-dimensional barrier, by emitting protons. A flurry of experimental activity studying this decay mode (some of it summarized in “Beyond the Proton Drip Line,” at left) has resulted in the complete delineation of the drip line up to scandium ($Z = 21$) and, for odd-Z nuclei, up to indium ($Z = 49$). A large number of proton emitters have also been discovered between indium and bismuth ($Z = 83$), and we have achieved a quantitative understanding of the properties of the decaying nuclei, such as their half-lives. Deformation has also been found to affect proton decay significantly.

A new mode of nuclear decay, direct two-proton emission, has been shown to occur in ^{18}Ne (see Figure 2.12). This mode was predicted decades ago, but until recently, experimental efforts had found only sequential emission through an intermediate state, a mechanism energetically forbidden in the case of ^{18}Ne. The characterization of the

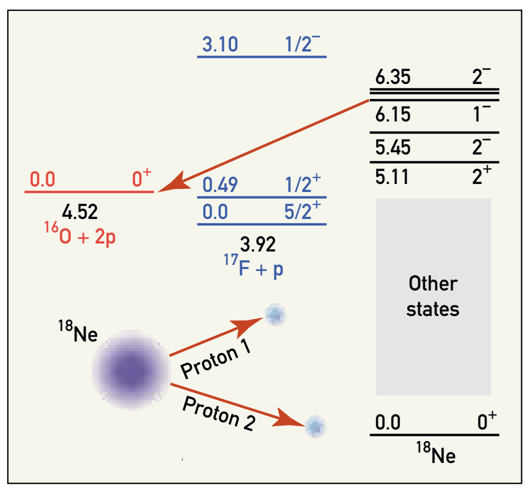


Figure 2.12. A rare event. Two-proton decay, one of the most exotic and elusive nuclear decay modes, has recently been observed in ^{18}Ne. As seen from the energy relationship between ^{16}O, ^{17}F, and ^{18}Ne, emitting one proton after the other, first from ^{18}Ne to yield ^{17}F and then from ^{17}F to give ^{16}O, is forbidden for ^{18}Ne states up to 6.4 MeV. The measured angular correlations between emitted protons, along with their relative energy distributions, give the first evidence of the two-proton decay, indicated by the long red arrow, of an excited state of ^{18}Ne at 6.15 MeV.

proton spectra will provide new insight into two-particle correlations and superconductivity in nuclei. First signatures of a new form of pairing have been seen in nuclei with $A > 60$ having equal numbers of protons and neutrons. However, intense beams from RIA will be necessary to explore the unique structure of these nuclei, as well as other heavy $N = Z$ systems.

In the short term, the exploration of particle-stable nuclei at or near the proton drip line with $Z > 50$ will continue, emphasizing mostly the regions where calculations predict the onset of deformation. In particular, the region above ^{208}Pb, where the Coulomb field is the strongest, will be the focus of attention. The opportunity to study proton emitters and beta-delayed proton emitters in lighter nuclei ($Z < 50$) has recently improved significantly, and research will concentrate on rp-process nuclei near the $N = Z$ line.

Neutron-rich nuclei: The physics of weak binding. At present, the question of which combinations of protons and neutrons form a bound nucleus has not been answered experimentally for most of the nuclear chart because of the lack of experimental access to most neutron-rich nuclei. At the dawn of a new century, these neutron-rich nuclei are increasingly the focus of experimental and theoretical investigations, as they promise to shed new light on the nuclear many-body problem. They also offer a unique terrestrial laboratory for studying neutron-rich matter, and as such, their properties represent invaluable input into pressing astrophysics problems, such as r-process nucleosynthesis and the characterization of the crusts of neutron stars. The fact that the limit of nuclear existence is experimentally unknown for all but the eight lightest elements illustrates both the experimental difficulty of accessing neutron-rich nuclei and the bright prospects at new and planned accelerator facilities.

The valence neutrons of some of the most neutron-rich light nuclei have density distributions that extend far beyond the nuclear core. For example, the spatial extent of ^{11}Li with 3 protons is similar to that of ^{208}Pb with 82 protons. Such neutron "halos" have now been found in nuclei as heavy as ^{19}C. Nuclei with two neutrons in their halos (such as ^{11}Li and ^{12}Be) have provided insight into a new topology with a so-called "Borromean" property, where the two-body subsystems of the stable three-body system are all unstable. As illustrated in Figure 2.13, recently developed techniques have begun to probe the wave functions of the ground state and excited levels in these halo nuclei.

The weak binding inherent in nuclei at the drip lines is likely to have a profound influence on all nuclear properties. The underlying shell structure, which responds to the presence of weakly bound states and diffuse matter, is significantly affected. In addition to changes in the radial behavior of the potential binding the nucleons together, the spin-orbit force, which is crucially important for the determination of the magic shell closures, is expected to decrease near the neutron drip line. Recent calculations suggest that the neutron-level structure may be significantly modified near the drip line, leading to new magic numbers. Indeed, in the limited region of neutron-rich nuclei accessible to date, a weakening of the $N = 8$, 20, and 28 shell closures and a reordering of orbitals have been observed, while $N = 16$ has emerged as a new shell gap. As noted above, the low binding energy of the outermost neutrons leads to extended and diffuse neutron distributions (halos or skins). In these regions of weak binding, pairing forces are expected to take on increased importance, as the continuum of unbound states is available for pair scattering. Other forms of nucle-

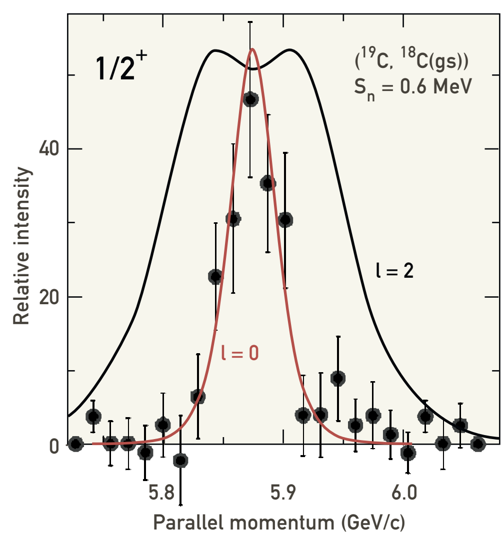


Figure 2.13. Nuclear halos. These results illustrate an example of a "knock-out" reaction as a means for studying neutron-rich "halo" nuclei. A high-energy halo nucleus, in this case ^{19}C, strikes a target, losing a neutron. Events that populate the ground state of ^{18}C are then selected. The shape of the recorded events, plotted as a function of momentum, is sensitive to the angular momentum of the removed neutron. In this example, the data clearly favor zero angular momentum. In this way, detailed information on the wave functions of the halo neutrons can be extracted.

onic correlations or aggregations may develop within a neutron skin. In short, strong pairing, quenched shell structure, and differences in proton and neutron density distributions will likely affect every nuclear property, and even the concept of single-particle motion in the nucleus, the cornerstone of most models of low-energy nuclear structure, may lose its validity.

Within the next five years, we are likely to establish the limits of existence for neutron-rich nuclei for all elements lighter than sulfur ($Z = 16$). This will double the number of elements for which the neutron drip line has been determined experimentally and will thus end the long quest to advance beyond oxygen. Measurements of nuclear masses away from stability will then take center stage, as they will serve as the first stringent tests of relevant nuclear models and provide indications of new regions of collectivity or of new shell closures. Measurements of the properties of the first few excited states will soon follow, as will searches for extended nuclear halo systems (some possibly possessing more than two valence neutrons), together with experiments aimed at finding predicted new modes of collective excitation, such as the soft dipole resonance mode.

The long-term future in the study of neutron-rich nuclei is again linked to the availability of RIA. With this facility, the limits of nuclear existence will be determined for elements up to manganese ($Z = 25$) and, depending on the exact location of the neutron drip line, perhaps all the way to zirconium ($Z = 40$). For heavier nuclei, RIA will establish nuclear existence and binding along isotopic chains 10 to 20 neutrons beyond the heaviest nucleus identified to date. This will provide the stringent constraints required for more accurate predictions and for extrapolations of the neutron drip line. With its extended reach for neutron-rich exotic beams, RIA will also determine fundamental nuclear properties such as mass, radius, and shape, providing additional experimental signatures for testing theoretical descriptions of neutron-rich nuclei. It will also offer the opportunity to probe such nuclei along the path of the astrophysical r-process.

The intensities to be provided by RIA ensure that halo nuclei in the vicinity of the drip line will be accessible to experiment, not only up to mass $A \sim 50$, where first theoretical predictions exist (^{34}Ne, ^{42}Mg, ^{44,46}Si, . . .), but also for nuclei with masses closer to 100, where the presence of such structures is a subject of much theoretical debate. RIA beams will also provide the necessary tools to study nuclei with exotic topologies. For example, the onset of the skin and its dependence on neutron number, as well as structural evolution, single-particle structure, and collective modes, will be investigated by studying a small number of selected isotopic chains that encompass large differences in N/Z ratios. The nuclei in the zinc, krypton, or zirconium chains are good candidates for such studies. At RIA, nuclei as neutron-rich as ^{90}Zn, ^{108}Kr, and ^{122}Zr (with 20, 22, and 24 neutrons more than the heaviest stable isotopes in the respective chains) will be available at rates of 0.01 s^{-1}, where experiments have already been proved feasible.

To accurately evaluate possible alterations to shell structure, it is important to determine such structure in the first place. Current knowledge is based mostly on the single-particle levels of a few nuclei near good closed shells—for example, ^{208}Pb. We now have a unique opportunity to improve on this situation, especially in the neutron-rich sector. Beams of the neutron-rich, doubly-magic ^{132}Sn nucleus are just becoming available and will be produced copiously at RIA. Usable beams of the recently discovered doubly-magic ^{78}Ni, the semiclosed-shell nucleus ^{60}Ca, and their neighbors will also be produced at RIA—yielding essential information about single-particle states, the occupation of these states by nucleons, and the interactions among these nucleons.

The heaviest elements. Investigations of the heaviest nuclei probe the role of the Coulomb force and its interplay with quantal shell effects in determining the boundaries of the nuclear landscape. The discovery of new elements with $Z = 110$–112 during the last decade, where alpha-decay chains link the new isotopes to known nuclei, thus assuring correct element identification, has been augmented recently by the tentative production of even heavier elements. In these instances, assignments are at present less certain, because the new decay sequences end in as-yet-unknown nuclei, and the customary confirmation experiments have not yet been carried out.

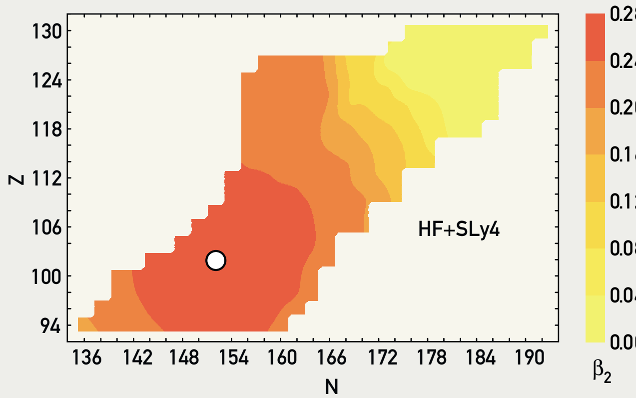
By coupling Gammasphere, the most powerful gamma-ray spectrometer, with a recoil separator capable of detecting weak reaction products, spectral information has been obtained for the first time for an element with $Z > 100$. The observation of a rotational band in ^{254}No (see “Spinning Heavy Elements,” page 40) confirms the prediction that this nucleus is considerably deformed. Calorimetry data also demonstrate the remarkable stability of such heavy, fissile nuclei in the presence of sizable angular momenta.

Spinning Heavy Elements

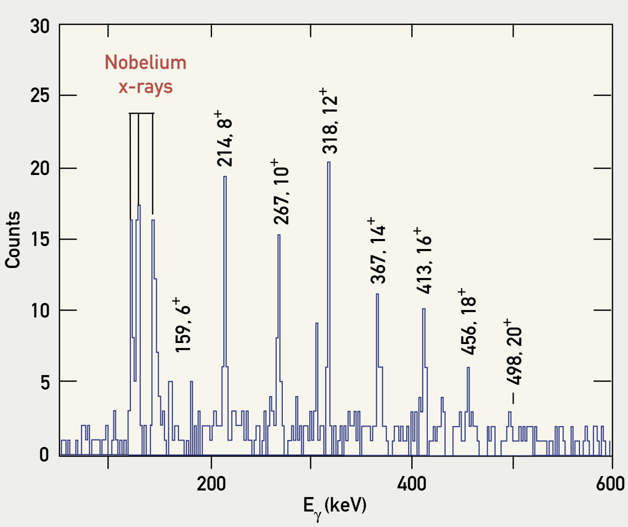
If nuclei behaved like two-fluid proton-neutron droplets, elements with atomic numbers greater than, say, $Z = 100$ would not exist, since the strong Coulomb repulsion would result in instantaneous fission. But "superheavy" elements with atomic numbers as high as 112 have already been synthesized, and their relative stability is a striking example of nuclear shell structure, which provides the additional binding energy needed to overcome the disruptive Coulomb force. Modern nuclear structure calculations—such as the one reflected in the figure to the right—not only predict which combinations of protons and neutrons can be made into heavy nuclei, but also indicate that stability arises in specific cases from the ability of the nucleus to deform.

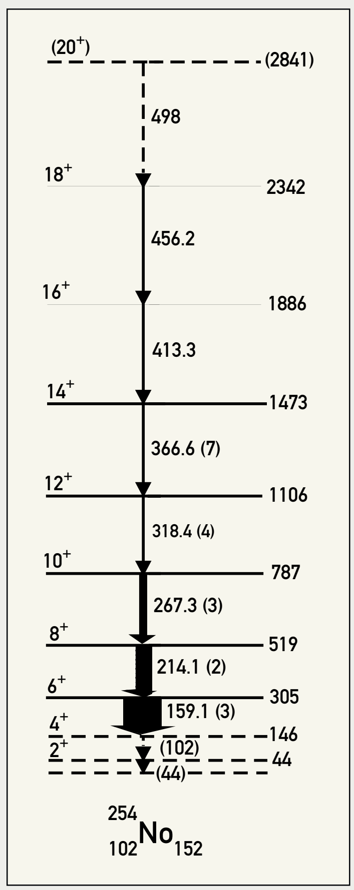
Experimental confirmation of the role of deformation in a heavy nucleus was recently obtained for ^{254}No, a nucleus with 102 protons and 152 neutrons (open circle in the figure). The measured spectrum of gamma rays, almost equally spaced in energy (see spectrum, below left), corresponds to a cascade of transitions characteristic of the rotation of a deformed nucleus, as depicted in the schematic to the right of the spectrum. From the precise energy differences between successive states, it was inferred that ^{254}No has a football-like shape with an axis ratio of 4:3, in agreement with theory ($\beta_2 \sim 0.3$). The fact that states with up to 20 units of angular momentum were detected underscores the remarkable resilience of the shell effects against centrifugal force and fission.

The success of this measurement is due to the combined use of Gammasphere, a powerful array of gamma-ray detectors, and the Argonne Fragment Mass Analyzer, a device designed to separate and detect heavy reaction products. The simultaneous operation of the two instruments proved essential in detecting the weak signals of interest, as the nuclear reaction producing ^{254}No is some ten thousand times less likely than other reactions occurring at the same time.



Stability from deformation. The colors in this plot indicate the degree of deformation, as measured by the quadrupole deformation β_2, predicted by a theoretical model labeled as HF + SLy4. The larger the value of β_2, the greater the prolate deformation of the nucleus. The open circle shows the location of ^{254}No.





Gamma rays from spinning nobelium. The spectrum of gamma-ray emissions (far left) from spinning nobelium, measured by Gammasphere, corresponds to a series of transitions in a rotating nucleus (near left). In the energy-level diagram, the widths of the arrows indicate the intensities of the electromagnetic transitions. The inferred deformation, corresponding to $\beta_2 \sim 0.3$, agrees well with theory.

Much progress in this field can be expected in the next five years. New experiments on elements above $Z = 112$ have already begun, using stable beams. In the more distant future, intense, exotic beams from RIA will complement and extend the present stable-beam program in at least two ways. First, they will help delineate the center of shell stabilization in superheavy nuclei through the formation of many new, neutron-rich isotopes. And second, RIA will make a significant contribution to the firm identification of the new superheavy elements created in fusion reactions with stable beams, since neutron-rich beams will allow the formation and study of many of the unknown members of the decay chains mentioned above.

Probing the Nuclear Equation of State

The equation of state (EOS), that is, the dependence of the internal pressure on density and temperature, is fundamental to the description of any fluid. The search for the nuclear EOS is motivated by aspects unique to the physics of the nucleus, especially the fact that it can be viewed as a two-fluid quantal droplet. Small-amplitude vibrations of the nucleus correspond to nearly harmonic density oscillations about the equilibrium density $\rho_0 \cong 0.16$ nucleons fm^{-3}. For density variations close to ρ_0, the nuclear EOS has been explored by exciting the nuclear giant resonances (that is, high-frequency nuclear vibrations). Recently, studies of these giant resonances have considerably narrowed the experimental range of nuclear incompressibility, and through such studies, new information has emerged pertaining to the radii of neutron distributions in nuclei. However, large uncertainties still exist for much larger density variations, where new phenomena occur and where new experimental techniques are needed to understand them.

The behavior of nuclei undergoing large oscillations in shape depends on how the nuclei respond to changes in their density and on the effects of differences in neutron and proton numbers (isospin asymmetry). For nuclei in a low-density regime, there is a critical temperature where two phases, liquid and gaseous, appear simultaneously. As the system enters this region in a collision between heavy ions, it becomes mechanically unstable and breaks up into liquid droplets embedded in a vapor. The very coexistence of the liquid and gas phases implies the formation of clusters for which important scaling laws have now been proposed (see “Nuclear Phases,” pages 34–35). These laws successfully describe available data on the yields of various isotopes and on the numbers of fragments produced in these collisions, as functions of the difference in the numbers of protons and neutrons in the colliding systems. The quantitative relationship between the scaling law parameters and the EOS at low density is a subject of great current interest.

The compressibility of nuclear matter in the high-density regime is an important quantity that strongly influences the structure of neutron stars, their stability against gravitational collapse, their production during supernovae explosions, and their manner of cooling afterwards (see also pages 57–61). Studies of the compression and expansion of nuclear matter in energetic nucleus-nucleus collisions have recently provided significant constraints on the EOS at high density in systems with equal numbers of protons and neutrons. However, comparable experimental constraints do not yet exist for the isospin dependence of the EOS, which is a critical ingredient for calculating the density profiles of neutron stars and the pressures supporting them against gravitational collapse. Although studies of this isospin dependence are still in their infancy, they are poised for rapid growth, as the required range of projectile-target combinations will be available with the intermediate-energy, exotic proton- and neutron-rich beams at RIA.

Outlook

Since the 1996 long-range plan, all areas of nuclear structure research have witnessed major theoretical and experimental advances. These include areas related to the understanding of single-particle and collective modes and their interplay at low and high spin, the description of structural evolution with proton and neutron number, the delineation of the limits of nuclear existence, the unraveling of the properties and topologies of exotic nuclei, and the investigation of nuclear matter under density oscillations. As underscored in this section, however, while much has been learned about the atomic nucleus, crucial questions remain. To address these questions fully, a number of new initiatives are essential.

The nuclear science community has identified the *Rare Isotope Accelerator* as its highest priority for major new construction. This is a major initiative: RIA will become one of the cornerstones of nuclear science in the U.S. It will have a dramatic impact on several subfields of nuclear science, but its effect on nuclear structure studies will be extraordinary. This bold new concept will define and map the limits of nuclear existence; make possible the exploration of the exotic quantal systems that inhabit these boundaries; and isolate, amplify, or reveal new phenomena, new types of nucleonic aggregations, and key interactions in ways that stable beams cannot. RIA will provide new foundations for the understanding of nuclei. It offers the promise to guide the development of a unified theory of the nucleus in which both the familiar properties and excitation modes of the nuclei at or near stability and the exotic structures far from stability may be encompassed in a single theoretical framework.

RIA is a project of such a scale that it is likely to operate toward the end or after the period covered by this Plan (fiscal years 2002–12). However, because of its importance to the future of the field, its influence will be felt immediately. For a timely start of construction, it is essential that the necessary technical developments be carried out expeditiously during the coming years. It is also necessary to develop the theoretical concepts and the experimental techniques required to fully realize the discovery potential of RIA. Most importantly, the scientific community that will use RIA must be nurtured at universities and national laboratories.

In the short term, the keys to progress in understanding nuclear structure are linked to the continued, vigorous exploitation of existing stable-beam facilities and of the first-generation exotic-beam facilities that are just now coming on-line. These facilities are critical to the pursuit of current exciting initiatives and promising physics themes. Stable and exotic beams are essential for the training of young scientists who will work in this field now and at RIA in the future, and who will meet national needs in high-technology areas such as medicine, stockpile stewardship, and energy production. Vigorous exploitation of these facilities requires funding at a level necessary to operate efficiently. While every effort must be made by the laboratories and universities to maximize productivity, it is clear that funding is currently inadequate to fully operate these very cost-effective facilities. The *Facilities Initiative,* which addresses this issue, is an essential component of this Plan.

Instrumentation is an area where new developments will enhance ongoing scientific productivity and pave the way for RIA. The success of Gammasphere has demonstrated that state-of-the-art instrumentation has a dramatic effect on the rate of scientific progress. New instrumentation initiatives should be encouraged, including but not limited to a *4π Gamma-Ray Tracking Array,* presented as part of this Plan.

Equally important to the vitality of nuclear structure research is increased support for theoretical investigations. The development of new concepts and methods is essential as an inspiration for the experimental program and for the interpretation of the fascinating and unexpected observations that will surely emerge. Exceptional progress has been made in recent years with very limited resources, both human and fiscal, thanks to radically new approaches and to the power of modern computing techniques. To take full advantage of the exciting science opportunities, especially in the context of RIA, a theory initiative is needed. A number of excellent suggestions to strengthen the nuclear structure theory program have been put forth. They are presented in the *Nuclear Theory Initiative* and the *Large-Scale Computing Initiative.*

This section has discussed the most basic question facing nuclear scientists: What is the structure of the nucleus? While many facets of the nucleus have been uncovered, much remains to be done, and the pace of discovery is rapid. For this reason, a coordinated framework for nuclear science research in the U.S. must maintain a vigorous program in this fundamental area. The 1996 long-range plan challenged the nuclear science community to develop a cost-effective proposal for an exotic-beam accelerator. The RIA concept not only meets this challenge, but also exceeds the performance expectations set at that time. RIA will provide the U.S. with the opportunity to assume a leadership role in nuclear structure physics for the coming decades. With RIA, the outlook for nuclear structure research is indeed a bright one.

QCD at High Energy Densities:

Exploring the Nature of Hot Nuclear Matter

Overview: In Pursuit of the Quark-Gluon Plasma

One of the fundamental tasks of modern nuclear physics is to understand the structure of the vacuum and the long-distance behavior of the strong interaction, one of the four basic interactions of nature. Quantum chromodynamics (QCD) is the current theory of the strong interaction in the context of the Standard Model of particle physics. However, many of the primary features of our universe are not easily understood from the form and symmetries of the Standard Model. In fact, a rather startling view of the vacuum arises when one examines the long-distance behavior of QCD. The vacuum—rather than being empty—is composed of a quark condensate that fills all of space, breaking the symmetries of the Standard Model and giving rise to the large masses of hadrons as compared with the light quarks (see "Chiral Symmetry, Mass, and the Vacuum," pages 46–47). It is a remarkable fact that the proton, made primarily of three light quarks, has a mass two orders of magnitude larger than its quark constituents; most of the proton's mass comes from its coupling to the quark condensate that fills the QCD vacuum.

Can we change the properties of the vacuum experimentally? Lattice QCD calculations argue that this is possible. When the vacuum "melts" at temperatures exceeding 170 MeV, the underlying symmetries of QCD will be restored. At these temperatures, matter should behave as a plasma of nearly massless quarks and gluons—the quark-gluon plasma, a state that existed in the first few microseconds after the Big Bang.

The vacuum, and in fact any system of quarks and gluons, is likely to have a complex phase structure, similar to that of many other bulk materials. The QCD phase diagram, as envisioned in current theory, is shown in Figure 2.14. The phase structure of the vacuum state is along the vertical axis where the baryon density is zero. There are actually two related phase transitions. The first is that of deconfinement, in which the quarks and gluons become free of their bondage in baryons and mesons. The second is that of chiral symmetry restoration, in which the masses of the quarks are reduced to their bare quark values. At temperatures above the chiral phase transition, the sum of the masses of the three quarks that make up the proton would be very small. It is still an open question as to whether these two phase transitions occur under exactly the same conditions of pressure and temperature.

The collisions of heavy ions produce matter with a range of energy densities and baryon densities corresponding to the two axes of the phase diagram in Figure 2.14. We expect

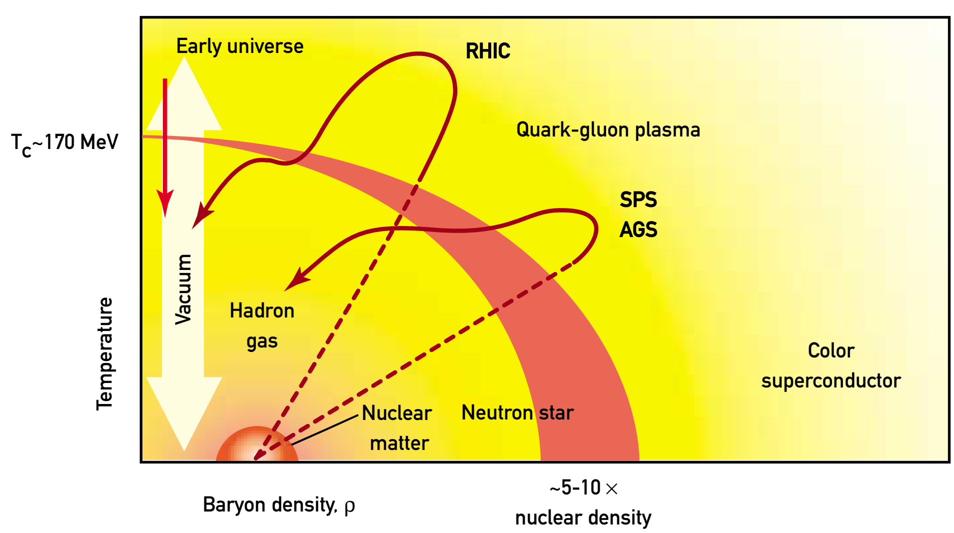


Figure 2.14. The phases of QCD. The QCD phase diagram, with baryon density as the abscissa and temperature as the ordinate. The red band indicates the range of temperatures and baryon densities at which phase transitions (both chiral and deconfinement) are thought to occur. The vacuum is the region near the *y*-axis, with a net baryon density near zero. Trajectories are also shown for systems created at the AGS and SPS, with center-of-mass energies of approximately 4–20 GeV per nucleon pair, and at RHIC, with a center-of-mass energy of 200 GeV per nucleon pair. The region of cold, high-density color-superconducting matter is shown to the far right.

both the deconfinement phase transition, and the chiral phase transition to occur in regions of either high energy density or high baryon density. Theoretical calculations on the lattice predict the location of the phase transition at low baryon densities to be at about 1 GeV fm^{-3}, or 170 MeV, as mentioned above. Theoretical calculations for nonzero baryon densities are much less certain, and only general estimates can be made. In experiments at lower energies, nuclei collide and essentially stop, producing systems of high baryon density. At the much higher energies provided by colliders such as RHIC, the nuclei pass through each other leaving behind high-energy-density debris with almost zero baryon density—essentially a highly heated vacuum.

In the context of this general picture, we have posed a number of fundamental questions:

- In relativistic heavy-ion collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?
- Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools? What is the origin of confinement?
- What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons? What is the origin of chiral symmetry breaking?
- What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

Achievements in relativistic heavy-ion physics. As implied in these questions, we are seeking to uncover many of the secrets of QCD with relativistic heavy-ion collisions (see "Anatomy of a Heavy-Ion Collision," pages 48–49). The U.S. program in relativistic heavy-ion physics, until recently based on fixed-target machines, has a long history. The first such machine was Berkeley Lab's Bevalac, which operated with a center-of-mass energy of about 2.5 GeV per nucleon pair. This was followed by the AGS at Brookhaven (~5 GeV per nucleon pair) and the SPS at CERN (~20 GeV per nucleon pair), where a substantial contingent of U.S. nuclear scientists collaborated. A new frontier has now been opened at RHIC, a colliding-beam machine with a center-of-mass energy up to 200 GeV, producing matter in a regime where lattice calculations are expected to be reliable. QCD has yielded its secrets grudgingly. Even in the perturbative regime where theoretical calculations are straightforward, the physics community did not immediately accept experimental evidence for gluons. A number of expected signals for the formation of the quark-gluon plasma have been observed in fixed-target experiments at CERN (and some at the AGS), but the evidence is not unambiguous. RHIC, with its broad range of accessible phenomena, can be expected to resolve many of these uncertainties—and indeed, early findings are tantalizing. But the flow of results has just begun, and conclusions are still tentative.

The most important recent achievements pertinent to the questions raised above include the following:

- Studies of particle abundances and spectra—as well as Bose-Einstein correlations, which give information about the space-time evolution of the collision—indicate that, in a nucleus-nucleus collision, the system undergoes rapid expansion and is close to both chemical and thermal equilibrium. Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs. However, interaction cross sections arising from colored quarks and gluons are expected to be larger and could be driving this rapid thermalization.
- A state of matter in which quarks and gluons are mobile is expected to show a strong enhancement of strangeness production, particularly antistrange particles whose yield would ordinarily be suppressed by their relatively large masses. Experiments at CERN have seen enhanced strange antibaryon production, with increasing enhancement for each additional unit of strangeness. Recently, a similar strangeness enhancement has also been observed at RHIC. Experiments at the AGS, which have been able to detect only the $\bar{\Lambda}$, have seen a strong enhancement in the $\bar{\Lambda}$-to-$\bar{p}$ ratio.
- In 1985 charmonium ($c\bar{c}$) production was suggested as a probe of a deconfined medium created in relativistic heavy-ion collisions. Quarks and gluons in the medium would screen the strong interaction between charm and anticharm quarks and thus cause the ($c\bar{c}$) pair created by hard nucleon-nucleon scatterings to "melt." This occurrence depends on the energy density of the medium and the species of charmonium being consid-

ered, with the less tightly bound χ and ψ' states breaking up at lower energy densities than the J/ψ. Just such a trend has been observed in experiments at CERN. However, uncertainties remain in the interpretation, because it is difficult to separate the contribution of charmonium suppression from other processes that produce similar effects.

- Signatures that may be interpreted as evidence of chiral symmetry restoration have also been seen. At CERN, excess electron-pair yields have been observed at invariant masses between 200 and 800 MeV, which can be explained as a mass shift of the ρ meson due to the onset of chiral symmetry restoration. Competing interpretations of the data as arising from collision-induced resonance broadening are also possible.

- Beginning in the summer of 2000, the first data were collected at RHIC in a run lasting three months, during which the machine reached 10% of its design luminosity, as planned. The center-of-mass energy during this run was 130 GeV per nucleon pair in gold-gold collisions. About 10^7 events were collected among the four RHIC detectors (see Figure 2.15 and "First Results at RHIC," pages 50–51). Much of this data has now been analyzed and published. During the fall of 2001, the full design luminosity was achieved, at the full energy of 200 GeV per nucleon pair, and 50–100 times as many events were collected.

- The multiplicity and transverse energy of particles produced in collisions at RHIC have been measured. These measurements provide an estimate of the energy density achieved, which was at least 20 times that of nuclear matter. The multiplicity was also measured as a function of the number of nucleons participating in the interactions. This provides a probe of the initial conditions for the collisions, which are believed to be a very high density of coherent gluon fields.

- One of the early, unexpected results at RHIC was the strong elliptic flow signal seen at relatively high momenta. Flow is a measure of the degree to which a group of particles moves collectively. Collective behavior can occur only if there is a strong degree of thermal equilibration. A strong elliptic flow indicates that this equilibration developed at very early times when the pressure was very large. Such an early thermalization, combined with the measured transverse energy, implies an energy density substantially higher than that required for the phase transition, as indicated by theoretical lattice calculations.

- The emission of hadrons with high transverse momenta is expected to be suppressed in a quark-gluon plasma, owing to the energy loss of partons. Such an effect was not observed in lower-energy collisions at CERN. Indeed, the opposite was found. However, at RHIC, the yield of high-transverse-momentum hadrons, measured in central nucleus-nucleus collisions, was

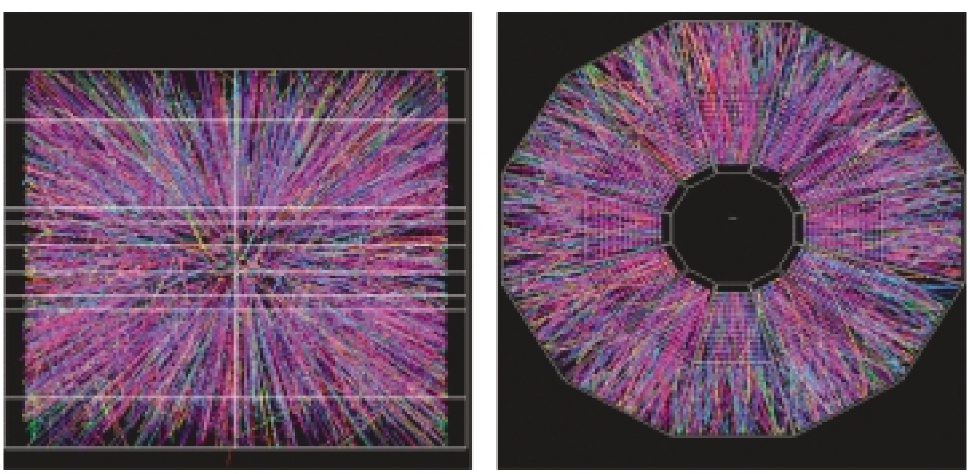


Figure 2.15. Golden glow. A central gold-gold event as seen in the STAR detector at RHIC. The side view and end view of the time-projection chamber are shown. Each colored radial line emanating from the center corresponds to the track of a particle produced in the collision. Such a central collision typically produces about 6000 particles.

substantially reduced as compared with that from ordinary proton-proton collisions.

- A major theoretical advance has also been made in a very different region of the phase diagram. In the very dense but very cold environment at the far right of Figure 2.14, quark matter is predicted to display many characteristics more familiar to a condensed-matter physicist than to a plasma physicist: Cooper pairs form, and the quark matter becomes a color superconductor, characterized by Meissner effects and gaps at the quark Fermi surfaces. Such cold quark matter may exist in the centers of neutron stars.

The years ahead: The RHIC era. Fixed-target experiments have clearly shown that heavy-ion collisions create high energy and high baryon densities. The density of hadrons is so large that there is simply not enough room for them to coexist as a superposition of ordinary hadrons. The observed signatures are not readily explainable by standard hadronic models. It is also clear that a great deal remains to be done in the energy regime accessible at the SPS. For example, a new experiment (NA60) is now under construction at CERN to measure the charm-production cross section, necessary to clarify the interpretation of the dilepton results.

In addition, we hope it will become possible to use astrophysical observations of neutron stars to learn more about the region of the QCD phase diagram occupied by dense, cold quark matter. Ultimately, information from astrophysical observations, data from the lower-energy experiments, and data on the hot quark-gluon plasma to be gained from experiments at RHIC must be pieced together into a coherent, unified phase diagram for QCD.

Notwithstanding the continuing promise of fixed-target experiments and astrophysical observations, the completion of RHIC at Brookhaven has ushered in a new era. Studies are now possible of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma. As the RHIC program matures, experiments will provide a unique window into the hot QCD vacuum, with opportunities for fundamental advances in the

Chiral Symmetry, Mass, and the Vacuum

Chiral symmetry is the symmetry between right-and left-handed objects, that is, between things that rotate clockwise and things that rotate counterclockwise. Physicists believe that the underlying rules governing the strong interaction is left-right—that is, chirally—symmetric. (The strong interaction is the force responsible for binding the atomic nucleus together.) The handedness of a particle is defined by the direction of the spin relative to the direction of motion. If one looks along a particle's direction of travel, a clockwise spin is defined as right-handed, a counterclockwise spin as left-handed. The flaw in this definition is that one can transform the coordinate system and change the definition of the spin, even while the intrinsic characteristics of the particle remain unaltered. Imagine an observer moving faster than the particle itself. He would see a "right-handed" particle moving in the *opposite* direction and would thus believe the particle to be left-handed.

In this case, it would be possible to change a right-left symmetric universe, one where half the particles are left-handed and half right-handed, into a universe in which all particles are right-handed—provided only that one had a very fast rocket ship. This would then spoil the chiral symmetry. How might this situation be avoided, so as to preserve chiral symmetry? One possibility is for all particles to be massless. It turns out that all massless particles move at the speed of light. Since nothing can move faster than the speed of light, no spin-redefining transformation is possible, and thus a universe of massless particles would be chirally symmetric. But of course, this doesn't match the universe that we see. Where then does mass come from?

Physicists believe that particles are, in their basic nature, massless and that they acquire mass through their interactions with the vacuum. This is the process of chiral symmetry breaking. QCD has the property that the lowest energy state is not empty space, but rather is a vacuum filled with a "condensate," which is itself composed of quarks. A computer simulation of this condition is shown at right. In turn, the interactions of quarks with this quark condensate conspire to make the quarks behave as if they have mass. This state of the universe depends on the temperature. If the understanding of quark confinement, chiral symmetry breaking, and, very possibly, new and unexpected phenomena in the realm of nuclear matter at the highest densities.

By colliding beams of ions from protons to gold, with center-of-mass energies from 20 to 200 GeV per nucleon pair, RHIC will create conditions favorable for melting the normal vacuum and creating states of matter unknown in the universe since the Big Bang. With these unique capabilities, RHIC addresses all of the fundamental questions posed on page 44. The U.S. thus now possesses the premier laboratory in which to study these questions. It is likely that an initial understanding of high-density QCD matter and its associated phase transitions will be achieved in the next several years. However, much will remain to be done after these initial discoveries.

By their very nature, phase transitions introduce a host of unusual phenomena—for example, critical phenomena leading to the formation of large-scale fluctuations. In addition, since there are actually two phase transitions, the chiral transition and the deconfinement transition, a great deal will remain to be understood about the relationship between the two. Furthermore, new puzzles will undoubtedly present themselves as we begin to understand more about the bulk behavior of QCD.

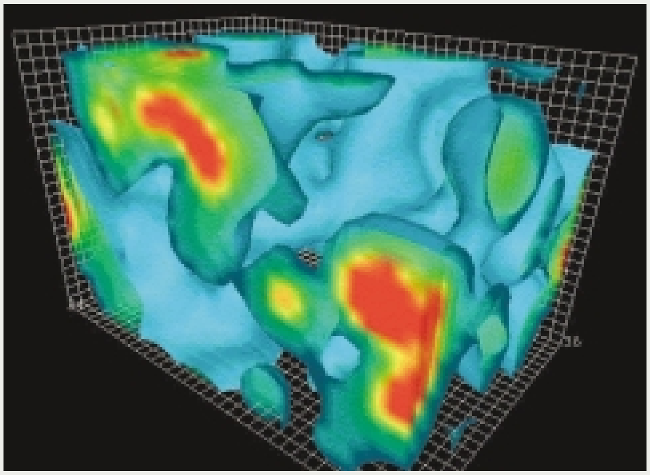
The following paragraphs discuss in more detail some of the opportunities that lie ahead.

Mimicking the Big Bang: Thermalization and Equilibration

The highly compressed, then rapidly expanding, nuclear matter created at RHIC, which has many of the characteristics of the early universe shortly after the Big Bang, is the system now available for answering the questions on page 44. Among them are questions of thermalization and equilibration: How do the systems created in these collisions evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved? Experiments will probe these questions by focusing on hadrons—on single-particle distributions and on correlations among parti-

temperature is high, as in the early universe—or in a relativistic heavy-ion collision—the vacuum state is such that the quarks once again exhibit their massless nature.

Although this seems to contradict the natural belief that space is empty, this is, in fact, an integral part of the Standard Model of particle physics—a model that has proved remarkably successful. Relativistic heavy-ion collisions offer the possibility of observing the effects of the vacuum directly, by heating it up and changing its characteristics, that is, by "melting" the vacuum.



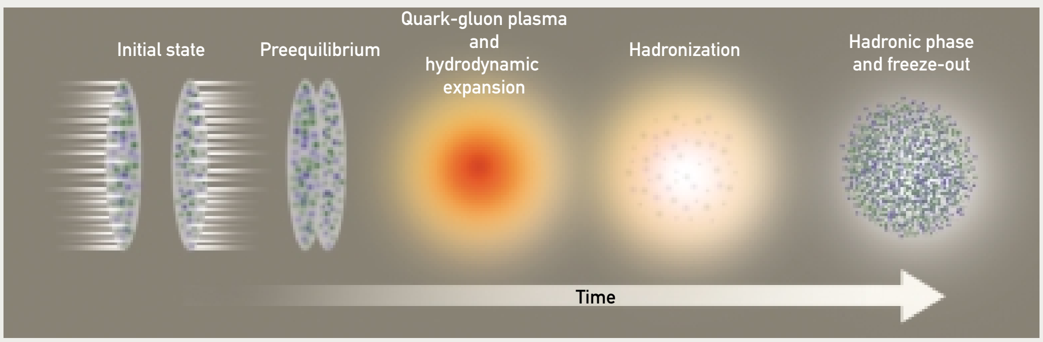
Simulating the vacuum. According to the Standard Model, all space is filled with the QCD condensate. The interaction of particles with this background condensate gives rise to most of the mass that makes up "ordinary" hadronic matter. The computer simulation shown here is a snapshot of the gluon field that binds quarks together to make up particles such as protons and neutrons. The red color indicates areas of intense "action" in the gluon field, associated with winding of the field lines. The green and blue colors correspond to weaker gluon field strengths. *Image courtesy of D. B. Leinweber, CSSM, University of Adelaide.*

Anatomy of a Heavy-Ion Collision

Relativistic heavy-ion collisions, such as those produced by Brookhaven's RHIC, provide physicists a chance to study very hot, dense matter similar to that which existed a few microseconds after the Big Bang. In a typical gold-gold collision, when viewed in the laboratory frame, the two nuclei initially appear as flat pancakes—a result of relativistic contraction (see the figure below). In the early preequilibrium phase, many "hard" collisions occur between the quarks and gluons of the nuclei, producing thousands of other quarks and gluons in an enormous cascade. The next stage of the collision is the one of primary interest. These secondary quarks and gluons equilibrate into a hot cauldron of matter, the quark-gluon plasma. Because of the low number of baryons (protons, neutrons, and their kin), this plasma is essentially a high-temperature vacuum. In the final stages, the plasma cools and condenses into ordinary particles, which are then seen by the detectors.

Head-on "central" collisions are the most violent sort, producing the largest number of "participants" and the largest volume of hot matter. More glancing "peripheral" collisions produce little, if any, hot matter, as suggested in the figure to the near right. However, these peripheral collisions are particularly important, since they can be used for comparison. The centrality of a collision can be monitored by detecting the cold "spectator" material.

In all these collisions, one of the most important questions is, How can one see if a plasma is made? One probe is provided by

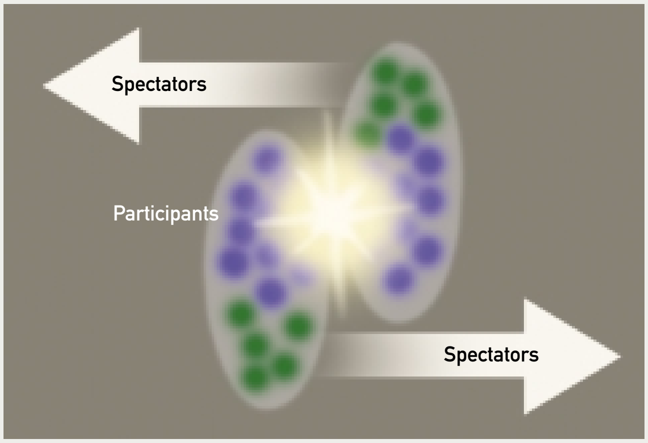


A Little Bang. Relativistic heavy-ion collisions replicate in the laboratory some of the conditions thought to exist a few microseconds after the Big Bang. In the schematic illustration here, two gold nuclei give rise to thousands of other quarks and gluons, which then equilibrate into a hot cauldron of matter, the quark-gluon plasma. As this plasma cools, it condenses into the ordinary particles seen by the detectors.

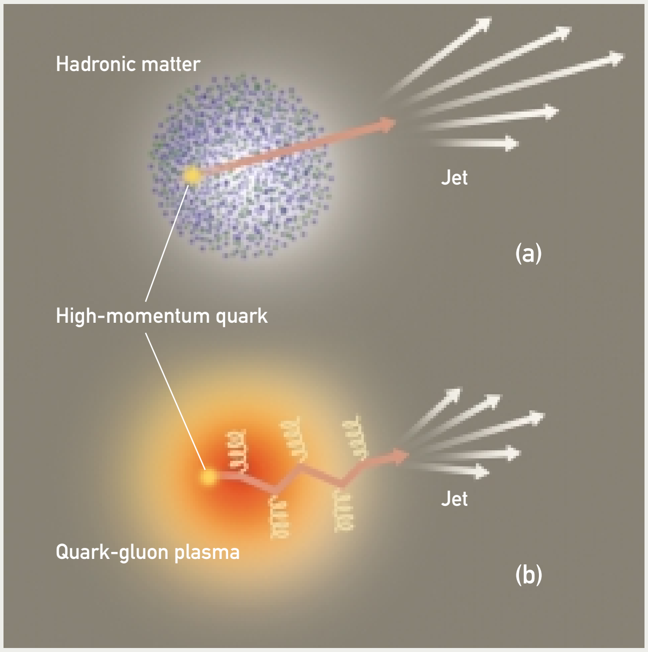
cles—and by detecting penetrating probes, which interact only electromagnetically and therefore escape the dense system relatively unperturbed. Theory, aimed at matching models and experimental data, will be crucial in understanding these measurements.

Extensive studies of lower-energy heavy-ion collisions, at the AGS and at CERN's SPS, have shown that the analysis of the distributions and correlations of soft hadrons yields the temperature and dynamics at the time the hadrons cease to interact, or "freeze out." The space-time evolution thus measured is crucial to understanding the collision dynamics, and it lends confidence to back-extrapolations to the early, hottest phase of the collision. Systematic study of the conditions under which the hadrons freeze out, as a function of initial temperature and collision volume, will help separate signatures of new physics from the underlying hadronic processes.

Momentum and flavor distributions of the hadrons provide information on the degree of thermal and chemical equilibration when the colliding system becomes dilute enough that hadronic strong interactions cease. When combined with other experimental information, such as thermal radiation, the space-time evolution of the entire collision can be inferred. An important goal at RHIC will be to determine whether equilibration occurs early in the collision, or only later, in the cooler hadronic phase. The complementary capabilities of the suite of RHIC detectors will be invaluable for this study, since they will allow us to combine measurements high-momentum particles. In the preequilibrium phase of the collision, some of the quarks acquire a very large momentum and thus appear as "jets" of particles. About half of the energy is carried by a single leading particle, which yields information about the momentum of the original quark as it left the collision region and before fragmenting into the particles that compose the jet. Fast quarks can traverse a region of ordinary hadronic matter with little hindrance (as illustrated schematically to the right); however, if the central hot region were a quark-gluon plasma, the fast quark would lose a great deal of energy, whereby the momentum of the leading particle would be greatly reduced. This leads to a "softening" of the momentum spectrum. Although it is too early to conclude that a quark-gluon plasma has been seen at RHIC, preliminary results of this sort suggest such a possibility and signify a spectacular beginning to the RHIC scientific program (see also "First Results at RHIC," pages 50–51).



A glancing blow. Not all collisions are head-on, or "central," collisions; a "peripheral" collision is shown here. The centrality of a collision can be determined experimentally by measuring the number of "spectator" particles.



Quarks and jets. Jets arise from high-momentum quarks that fragment into particles after they leave the collision region. If no quark-gluon plasma has been formed, as in (a), the quark passes though nuclear matter with little resistance. However, in the presence of a quark-gluon plasma, as in (b), high-momentum quarks lose a great deal of their initial energy, and the detected particles in a jet have considerably less momentum.

of hadronic observables, collective behavior reflecting early conditions, and thermal emission of virtual and real photons.

Early results from RHIC on some of these topics have already indicated that the system freezes out at a lower baryon density and at a somewhat higher temperature than at the SPS or AGS. As already mentioned, flow measurements indicate that the degree of thermalization is high; hence, the concepts of temperature and pressure have meaning in the system under study. More information will be coming as physicists refine their measurements.

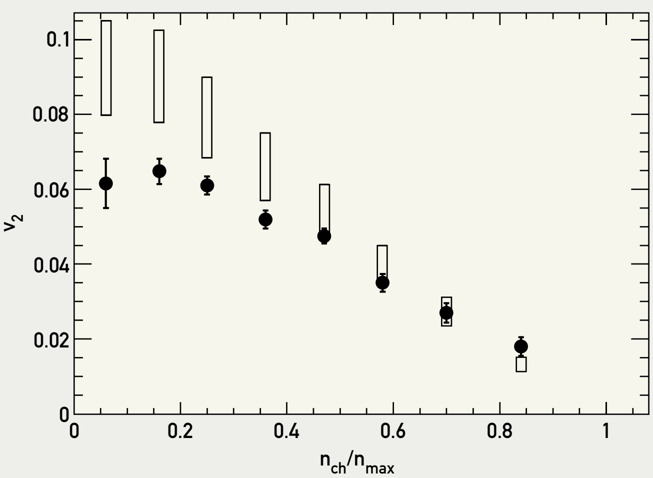
Real and virtual photons, materializing from quark-antiquark annihilations as electron or muon pairs, are radiated from the hot, dense QCD matter. Although such radiation is emitted at all times during the collision, for photons above about 100 MeV, the reaction dynamics significantly favors emission from the hottest part of the colliding system. (Detectors at RHIC are not currently sensitive to very low-energy photons.) Thus, measurements of the distribution of the black-body thermal radiation will yield the initial temperature. The background to such a signal is formidable, however, since photons and electrons are copiously produced from other sources as well, such as π^0 decay. Upgraded detectors designed to reject such backgrounds will be necessary in the future. Systematic analysis and variation of the initial conditions will also be required to solidify the interpretation.

First Results at RHIC

Construction began on RHIC in 1991 and was completed at the end of 1999. The first data-taking run commenced shortly thereafter. The second run, currently under way, is scheduled to conclude in early 2002. The four RHIC detectors were only partially instrumented for the first run but are now substantially complete. STAR is a large-acceptance detector built around a central time-projection chamber (TPC) in a solenoidal magnetic field. Inside the TPC is a silicon vertex tracker for detecting secondary vertices. The PHENIX detector is composed of four spectrometers optimized for detecting and identifying electrons, muons, photons, and hadrons. Multiple detector subsystems are used in the two central arms, yielding good momentum resolution and particle identification. Of particular note is redundancy in electron identification capabilities, giving a total e/π rejection of better than 10^{-4}. PHOBOS, one of two smaller detectors, is composed primarily of silicon and is optimized for large event rates. The second smaller detector, BRAHMS, specializes in measuring the fragmentation region of the collisions.

The early data have now been analyzed, and much has already been learned. Prior to the start of the RHIC experiments, very little was known about collisions of heavy ions at very high energies; for instance, predictions of the number of particles that would emerge from such a collision varied by a factor of four. Among the early findings are the following:

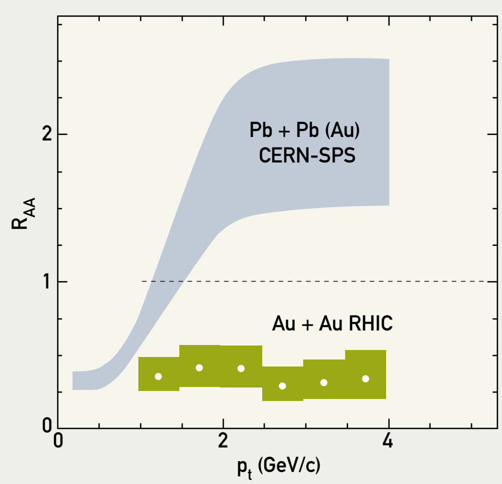
- The particle density in the hottest region in central gold-gold collisions was about a factor of two higher than previously achieved at CERN. A measurement of the transverse energy shows a similar result. Furthermore the yield per participant was found to increase with centrality, indicating the importance of hard processes and multiple collisions, which, assuming an early thermalization (as implied by the strong flow signal), would lead to energy densities greater than that required for the phase transition, as indicated in QCD lattice calculations.
- The azimuthal asymmetry of particle production in peripheral and semicentral collisions, known as elliptic flow, was found to be surprisingly large (as shown in the figure at the left)—evidence of a high degree of thermalization early in the collision, with a buildup of high pressure followed by a violent explosion. The magnitude of the flow agrees well with the predictions of hydrodynamic model predictions for a wide range of momenta and particle types. This important result supports the thermalization hypothesis.
- The antibaryon-to-baryon ratio was found to approach unity, in contrast to previous measurements at CERN, where the ratio was more than tenfold smaller. Fits to a thermal model of various particle yields lead to a very low baryo-chemical potential (consistent with a high antibaryon-to-baryon ratio), again substantially different from that observed at CERN. While not entirely baryon-free, these measurements indicate that at RHIC experiments are now in a region where lattice calculations are reliable and where the observed system should exhibit the characteristics of a vacuum at high temperature.
- One of the most intriguing results from the first run comes from a measurement of the transverse momentum spectrum for neutral pions, shown in the figure to the right. A fast-moving colored parton (quark or gluon) is a useful probe of hot nuclear matter. In normal nuclear matter, a quark would experience only a small energy loss; hence, the



Nuclear flow. The figure plots elliptic flow v_2 (solid points) as a function of centrality, defined as n_{ch}/n_{max}, as measured by the STAR detector. The open rectangles show a range of values expected for v_2 in the hydrodynamic limit, scaled from ε, the initial space eccentricity of the overlap region. The lower edges correspond to 0.19ε and the upper edges to 0.25ε. The startling feature of these data is that, for central events ($n_{ch}/n_{max} > 0.5$), the flow signal appears to be as strong as allowed by hydrodynamics, implying an early equilibration of the system.

resulting jet would carry essentially all of the energy originally imparted to the parton. In a quark-gluon plasma, however, the deconfined color fields would slow the parton down considerably; energy losses can be as great as 10 GeV fm^{-1}. This would lead in turn to a reduced yield of high-momentum particles—exactly the result observed at RHIC. Whether this is a definitive signal of a quark-gluon plasma, however, has not yet been determined. Future data will provide more statistics and higher transverse momenta, as well as proton-nucleus data for comparison.

The interpretation of all these findings, in terms of temperature, entropy production, and ultimately, the existence of a phase transition, will take some time. Early results on charmonium suppression, dilepton spectra, and multistrange antibaryons will require data taken during the 2001–02 run. In any case, this has been a spectacular beginning for the RHIC experiments.



Jet suppression. Plotted here as a function of transverse momentum is the ratio of the measured yield of neutral pions in nuclear collisions to the yield that would be expected based on extrapolation from proton-proton collisions. Results are plotted for gold-gold collisions at RHIC (lower data points) and for lead-lead and lead-gold collisions at CERN at lower energies (broad upper band). The colored bars around the RHIC data points indicate the level of systematic error. The results are qualitatively different: At CERN energies, the yield at large transverse momentum is enhanced, whereas at RHIC energies, it is depleted. Such a depletion was predicted on the basis of the expected energy loss of partons in a quark-gluon plasma. The results, therefore, provide intriguing indications that this state may have been formed in collisions at RHIC. Further experiments will be needed to confirm this interpretation.

Quarks and Gluons Unbound: Deconfinement

A second suite of unanswered questions is tied to the phenomenon of deconfinement. For example, Can signatures of the deconfinement phase transition be located in the cooling debris of relativistic heavy-ion collisions? And what is the origin of confinement? The fundamental degrees of freedom in QCD are quarks and gluons. However, free quarks and gluons have never been observed, and the physical spectrum of particles contains only hadrons—"colorless" bound states of quarks, antiquarks, and gluons. The origin of this "confinement" is linked to the properties of the vacuum. Numerical calculations on the space-time lattice have shown that, at high temperatures and densities, the vacuum structure of QCD may "melt," leading to a novel form of QCD matter in which quarks and gluons move freely—the quark-gluon plasma. Further progress in the theory, including both new analytical methods and improved simulations on the lattice, is imperative to confirm these predictions. Heavy-ion collisions create a hot and dense environment in which this transition may be induced experimentally. Connecting observations from these experiments to "signatures" of deconfinement is now a prime goal of the field.

One such signature is the suppression of high-momentum particles. Measurement of the hard-scattering processes via high-transverse-momentum hadrons and heavy-flavor distributions will indicate to what extent the fast particles lose energy in the dense medium. This energy loss results in energy transfer from fast particles to the medium and thus drives thermalization. Furthermore, this energy transfer multiplies the number of gluons and drives particle production, increasing the density of the medium further. In fact, some theoretical models predict that matter may reach the stage of gluon saturation, in which case the physics is determined by interactions in a dense gluon gas, calculable using perturbative QCD, with subsequent hydrodynamic expansion. Measured particle yields, spectra, and correlations to transverse momenta of at least 10 GeV/*c* are needed to determine whether such predictions are correct. As noted earlier, RHIC may already have revealed hints of this thermalization phenomenon in the π^0 and charged-hadron transverse momentum spectra. Further measurements, in the second year of data-taking, have just begun and should extend the spectra to a transverse momentum of 10 GeV/*c*. In addition, important comparison data will be taken in the coming years for proton-proton and proton-nucleus collisions.

At higher luminosities, it will be possible to directly measure the photons produced opposite the high-transverse-momentum hadrons. Since these photons recoil against the quark jets, and since they do not suffer energy loss in the deconfined medium, they serve as indicators of the initial transverse momenta of the jets. Such observations will provide a means to make careful, quantitative measurements of the energy loss. One interesting possibility is to "flavor tag" the high-transverse-momentum hadrons. A leading K^- with no valence quarks is more likely to come from a gluon jet. This would allow us to measure the difference in the energy loss between gluon and quark jets. Gluon jets are expected to lose energy at twice the rate of quark jets in a deconfined medium. Later in the decade, the LHC will be able to make similar measurements at 30 times the center-of-mass energy available at RHIC, where the lifetime of the quark-gluon plasma is expected to be several times longer and jet cross sections at high transverse momentum are two to three orders of magnitude greater.

J/ψ suppression is another well-known proposed signature of deconfinement. RHIC will be able to measure J/ψ production in both the muon and electron channels. One of the crucial measurements that must accompany the measurement of the J/ψ is that of open charm production. To make this possible, specialized vertex detectors must be constructed, with the position resolution needed to discriminate between the charm vertex and the original event vertex. R&D programs focused on such an upgrade are under way.

The J/ψ is but one of the vector mesons in the charm family. The excited states of the J/ψ, as well as the Υ family (bound states of $b\bar{b}$), should all exhibit some degree of suppression. The suppression of the associated states, χ_b and χ_c, can also be observed, since they decay to the detectable vector mesons. Each of these states should melt at a different temperature. In fact, the Υ will be used as a control, since it should not be suppressed at all at RHIC energies. By varying the temperature and volume of the system by means of changes in beam energy and species, we can change the pattern of suppression of the various states. Not only would this be a convincing signature of a phase transition, but it would also give a good measure of the actual energy density. This will require a higher luminosity than currently available at RHIC, as in the proposal for RHIC II. In addition, when the LHC begins heavy-ion operation, the Υ family will be produced and detected at rates two to five time higher than at RHIC and will be easy to analyze.

Looking into the QCD Mirror: Exploring Symmetries

Investigations of chiral symmetry breaking respond directly to questions about the most fundamental properties of the QCD vacuum and its connections to the masses of the hadrons. The challenge for RHIC experiments is to search for evidence of in-medium mass changes among the low-mass vector mesons associated with the restoration of chiral symmetry. Direct, in-medium measurements of the masses of light vector mesons such as the ρ, ω, and ϕ are possible, since they decay rather rapidly within the fireball before hadronization. The decay to di-electrons is particularly interesting, since electrons should not be rescattered in the medium, and their invariant mass should reflect the mass of the vector meson in the altered vacuum state. Since some fraction of the vector mesons decay outside the medium (in the case of the ω, some 70–80% do so), these can be used as a calibration point for the measurement. The fraction exhibiting a shifted mass should change as a function of the transverse momentum and the size of the central fireball. This shift would be a particularly dramatic signature of the altered vacuum. Higher luminosities and improved detectors will be needed to reject background for detection of the ρ, the shortest lived, and hence the broadest, of the vector mesons. Observation of the ρ will be important, since it decays entirely within the fireball, and its spectrum may yield a history of the thermal evolution of the system.

The presence of a phase transition is also expected to cause inhomogeneities, which may survive the hadronic phase as fluctuations in particle number and type. Fluctuations and droplet formation are of particular interest, since similar processes may account for much of the large-scale structure of the universe and the inhomogeneities observed in the cosmic microwave background. Several fluctuations have been proposed as signatures of a phase transition. If the transition is first order, the growth of hadronic droplets and the shrinking of quark-gluon droplets may yield a lumpy final state and large fluctuations in particle number. Different scenarios may lead to other signatures, such as abnormal ratios of charged to neutral pions, or enhancements of pions at low momenta. Experiments will search for such phenomena and correlate their appearance with other signatures of the quark-gluon plasma.

The theory of chiral symmetry breaking and restoration is under active development. Progress requires the development of new analytical tools and further advances in lattice calculations. In order to investigate chiral symmetry on the lattice, we must be able to perform calculations with realistic quark masses. This places severe constraints on the size of the lattice and requires new methods (for example, "domain wall fermions") and new and more powerful computers.

Weak interactions violate both parity (P) and combinations of charge conjugation and parity (CP). By contrast, the strong interactions appear experimentally to preserve both of these symmetries under normal conditions. QCD as a theory does not require this. Therefore, it would be of great interest to learn whether CP-violating processes occur in the strong interactions under extreme conditions of high temperature and density. Theoretical progress in this area is linked to the understanding of topological effects in gauge theories at finite temperatures. This requires improvements in both analytical tools and lattice simulations. Clever experimental signatures have been devised for CP-violating bulk phenomena in heavy-ion collisions at RHIC. In theory, since CP is conserved in ordinary strong interactions, the signature of the altered CP state should be preserved during the evolution of the collision and may be quite distinct.

High-Density Matter

A final realm of investigation is the nature of matter at the highest energy densities. The behavior of QCD at the high-energy frontier is not yet understood theoretically. The simplest and most fundamental questions are still unanswered: Why do hadron cross sections rise at high energies? How are particles produced? What is the wave function of a high-energy hadron? RHIC will help find the answers to such questions by providing detailed data on particle production over a wide range of atomic numbers and energies. Progress in understanding high-energy behavior in QCD will, in turn, allow the reconstruction of the initial conditions in heavy-ion collisions, a crucial prerequisite to theoretical descriptions of the entire process. Such strides will require continuing development of theoretical tools, as well as large-scale, real-time Monte Carlo numerical simulations.

Gluonic interactions may be expected to dominate the first few fm/c of RHIC collisions, immediately following the initial nucleon-nucleon interactions as the nuclei penetrate one another. Gluon fusion processes dominate the production of charm and bottom quarks at energies attainable at RHIC. Consequently, measurements of open charm and bottom decays will likely be the most important ways to study the gluon fields inside heavy nuclei and their excitations in heavy-ion collisions. Of particular interest are distributions at low x, where x is a measure of the momentum fraction of a nucleon carried by an individual quark or gluon. These measurements require greater luminosity and detector efficiency than is currently available at RHIC. The RHIC II initiative addresses these two issues and will lead to a 40-fold increase in luminosity. RHIC II will be an invaluable tool to study the evolution of the quark structure functions to small x inside heavy nuclei (measurements of proton-nucleus collisions will yield this information), as the parton distributions evolve during a heavy-ion collision.

The dependence of the multiplicity upon the number of nucleons participating in the collisions was measured in the RHIC experiments. This dependence reflects the nature of the initial distribution of gluon fields inside the colliding nuclei. The early results provide support for a picture in which these fields are very dense and highly coherent, and in which the typical density scale of these fields inside nuclei is significantly greater than that inside a single nucleon.

Nuclear shadowing is another important process in understanding the initial stages of RHIC collisions. This can be measured directly via Drell-Yan and other hard processes in proton-nucleus collisions. Experiments must measure, with sufficient statistics, the dimuon distributions at high mass and the hadron spectra at high transverse momentum (at or above 10 GeV/c) to determine the extent of shadowing in kinematic regions accessible at RHIC. The results feed back, of course, into understanding the initial conditions in nucleus-nucleus collisions. However, they also probe the gluon field properties directly. If the gluon and quark densities can saturate, this will affect the gluon distribution deep inside a heavy nucleus, as well as the dynamics of the early stage of a heavy-ion collision. Measuring the intrinsic transverse momentum of the quarks within the nucleon via hard probes, and observing how this depends on x, as well as the volume of dense matter, can address the issue of saturation. All of these measurements require the capabilities of RHIC II. The LHC should have excellent capabilities to study this physics as well, since the apparent density of low-x virtual gluons will almost certainly be at saturation there.

A future electron-ion collider will make significant contributions to these measurements. Because of the Lorentz contraction, the nucleus will effectively amplify the parton densities seen by the incoming electron by a factor of the thickness of the ion, $\sim A^{1/3}$. Hence, lower center-of-mass energies are adequate for the observation of various phenomena such as gluon saturation. (In technical terms, one is able to reach thresholds for these interesting phenomena at higher values of x, the fraction of the nucleon momentum carried by the parton.)

Outlook

RHIC has just begun its task of uncovering the secrets of QCD. The next few years will yield a wealth of new information, and we have an outstanding opportunity to revolutionize our understanding of matter at the highest energy densities. Accordingly, the highest priority for the relativistic heavy-ion community is to utilize RHIC to its fullest potential. Sufficient running time is required to realize the physics promise of RHIC and to reap the rewards of our investment in RHIC's construction. This priority is also recognized in the first recommendation of this Plan and in the *Facilities Initiative* that supports it. Certain short-term upgrades are also essential, as well as R&D aimed at major upgrades to the machine luminosity and to the detectors. In the more distant future, significant upgrades of the collider and the experiments will be needed. An upgrade program such as the *RHIC II* initiative, which increases luminosity and adds new capabilities to the experiments, will allow in-depth pursuit of the most promising observables characterizing the deconfined state. Timely completion of the technical R&D is essential so that a detailed plan and schedule can be developed.

As discussed earlier, many open questions remain in the study of QCD at the high-energy frontier. Electron-nucleus collisions can provide complementary information to that obtained at RHIC. One of the technical options of the *Electron-Ion Collider* initiative would add this capability to the facility. This is an extremely exciting opportunity for the long term, since it allows access to a new regime within QCD and should shed light on the initial conditions for heavy-ion collisions at RHIC. As with RHIC II, R&D is essential in the near term so that a full scientific proposal can be developed.

Finally, the CERN heavy-ion program will be starting soon at the LHC. It would be wise to make a modest investment of manpower and money so that some U.S. participation is possible. This program should focus on those aspects of relativistic heavy-ion physics not easily addressed at RHIC. This includes jet and photon production at transverse momenta above 20 GeV/c, Υ family vector meson production, and W and Z production in heavy-ion collisions. The LHC offers jet and photon production rates one to three orders of magnitude larger than those at RHIC, for transverse momenta in the range 20–100 GeV/c, opening the door to detailed studies. The LHC also has a kinematical reach some 25 times better than RHIC's, extending into the realm of very soft gluons, where we may expect saturation effects to matter.

While the general structure of QCD is now firmly established, its properties are not yet fully understood. Many fundamental problems remain unsolved and are thus at the forefront of modern theoretical physics. One of the most important tools for making progress is lattice gauge theory, which allows us to solve complex nonlinear field theory problems using a computer. Such problems are among the most complex in computer science and require enormous computing power. New computational capabilities will be needed in order to make progress, both in interpreting experimental results and in furthering fundamental theoretical understanding. The necessary capabilities are contained within the *Large-Scale Computing Initiative*.

Nuclear Astrophysics:

The Origin of the Elements and the Evolution of Matter

Overview: Cosmic Questions

Fascination with the wonders of the cosmos and with the origins of life may be as old as our species. In the modern-day quest driven by this age-old fascination, nuclear physics plays a key role. The structure of atomic nuclei and the interactions among them govern the energy generated in stars such as our sun, making life on Earth possible. They also drive the evolution of stars and are responsible for the synthesis of the elements that constitute everything in the universe, from the components of our bodies to the most distant stars. The fact that the iron in our blood and the calcium of our bones had their origin inside a star is a dramatic reminder of the link between our lives and the cosmic scale of astrophysics.

This melding of nuclear physics and astrophysics has created the broad interdisciplinary field of nuclear astrophysics, a field that addresses some of the most compelling questions in nature:

- What are the origins of the elements necessary for life?
- How did the sun, the solar system, the stars, and our galaxy form, and how did they evolve?
- How much "ordinary" matter is there in the universe, and what is the remainder made up of?
- How old is the universe?

Nuclear physics plays a central role in seeking answers to these vital questions. Nuclear processes provide a window into the depths of the stellar interior, a place opaque to most other forms of inquiry. Nuclear processes also lead to violent explosions marking the destruction of some stars. Furthermore, they are keys to unlocking cosmological secrets such as the nature of the early universe, its evolution through time, its current large-scale structure, and its ultimate fate. Finally, since all of the elements were produced by nuclear reactions, nuclear physics is crucial to determining the chemical history of galaxies and the appearance and distribution of galactic radioactivity. Understanding such macroscopic phenomena, which involves deciphering the latest measurements from satellite- and ground-based observatories, thus requires knowledge of nuclear physics phenomena at microscopic scales.

Recent years have been a golden age for observation. Sophisticated satellite-based observatories, such as the Hubble Space Telescope, the Chandra X-ray Observatory, and the Compton Gamma Ray Observatory, have provided an unparalleled wealth of new, detailed astrophysical data. This trend will continue, since numerous ground- and spaced-based observatories are planned in the next decade. The observation and understanding of element-formation processes are among the highest scientific priorities for these planned observatories, which include gamma-ray observatories such as INTEGRAL and the Advanced Compton Telescope, optical observatories such as the Next Generation Space Telescope, probes of the cosmic microwave background such as MAP, and a number of large-aperture ground-based observatories. However, full realization of the opportunities afforded by these new instruments will be possible only if the underlying nuclear processes are well understood. Important complementary observations are being made at SNO, SuperKamiokande, and other huge subterranean caverns filled with water or special liquids and thousands of light detectors. These systems have glimpsed elusive neutrinos—from the sun and from exploding stars—and the results indicate that neutrinos contribute substantially to the mass of the universe (see also pages 77–83). Yet another complementary approach to cosmic observations is the extremely sensitive laboratory microanalysis of the elemental abundance distributions in tiny silicon carbide grains in meteorites, which have detected abundances that differ wildly from material normally found on Earth.

Recent achievements in nuclear astrophysics. Recent astrophysical observations have advanced in concert with laboratory nuclear physics and theoretical modeling of stellar phenomena. In the 75 years since nuclear processes were first postulated to occur in stars, significant progress has been made in determining the nuclear processing that occurs in various stellar environments. Recent advances in the technology of nuclear physics—such as the availability of beams of radioactive nuclei, large detector arrays, and underground accelerators—have enabled the measurement of some important, previously inaccessible nuclear reaction cross sections and nuclear properties. Some accomplishments since the 1996 long-range plan include the following:

- As discussed on pages 77–83, oscillations of neutrinos from one type to another have been confirmed as the key to resolving the puzzle of the "missing" solar neutrinos.
- Beams of radioactive nuclei have been used to make the first direct measurements of key nuclear reactions driving cataclysmic explosions in binary systems.
- A high-current, low-energy accelerator has been used to measure, for the first time, a charged-particle reaction at energies comparable to those occurring in the sun.
- Elegant experiments using stable and radioactive beams have fueled real progress in understanding the capture of alpha particles on ^{12}C and the capture of protons on ^{7}Be, which are of prime importance in the evolution of massive stars and in the core of the sun, respectively.
- By use of neutron beams, the fusion rates of neutrons and heavy elements have been newly determined, yielding the first precise confirmation of the theory that tiny grains in some meteorites originate in red giant stars.

The information from these experiments and others is being used in an emerging generation of sophisticated, computationally intensive models of astrophysical phenomena. These data are also being used to improve predictions of unmeasured nuclear reactions and nuclear structure.

Cosmic mysteries and a roadmap for solutions. In spite of these achievements and the tremendous progress in observations, today's understanding of many crucial astrophysical events is still in its infancy. Many mysteries about the nature and evolution of our universe remain unanswered. Among those that will be addressed in the coming decade are the following:

- Spectacular core-collapse supernova explosions represent the violent end of a massive star's life and create and disperse many elements—but the explosion mechanism remains elusive. Theoretical astrophysical modeling, coupled with results from a wide variety of nuclear physics measurements involving radioactive nuclei, will be required for progress in this area.
- Estimates of the amount of matter ejected from other explosions—novae—differ by an order of magnitude from observations. Measurements of reactions on proton-rich radioactive nuclei, coupled with improved astrophysical modeling, are needed to address this puzzle.
- The galaxy has been mapped with gamma rays from the decay of radioactive ^{26}Al, but we do not yet understand all the astrophysical events that create this radioisotope. Measurements of reactions on proton-rich radioactive nuclei are needed to clear up this mystery.
- With recently launched satellites like RXTE and the Chandra X-ray Observatory, a tremendous amount of new x-ray data from accreting neutron stars is being gathered, leading to discoveries of new phenomena such as oscillations and superbursts. Nuclear physics data on unstable, proton-rich nuclei are needed to interpret these observations and to reveal the properties of the underlying neutron star.
- It remains unclear where about half of the heavy elements are formed. Measurements of the structure and reactions of neutron-rich radioactive nuclei are required to answer this important question.
- The other half of the heavy elements are most likely formed in bloated red giants via the capture of neutrons, but we still do not understand the origin of the necessary neutrons. Measurements of alpha- and neutron-induced reactions, as well as improved astrophysical modeling, are needed to address this issue.
- Current models of element formation do not, in many cases, match the abundances that are now precisely measured in meteoritic grains—"stardust." Here, measurements of neutron-induced reactions are essential to progress.
- Recent measurements have confirmed the notion that different neutrino types "mix" with one another, but the nature of this mixing is still unknown. Improved neutrino measurements and measurements of a number of nuclear- and neutrino-induced reactions are needed here.

A number of facilities are currently available to investigate these mysteries. Radioactive-beam facilities, such as NSCL at Michigan State and HRIBF at Oak Ridge, will be invaluable in enhancing what we know of exploding stars.

Low-energy facilities, such as NSL at Notre Dame and LENA at TUNL (Duke), are vital for examining nonexplosive hydrogen and helium burning in stars like our sun and in red giants. Argonne, Berkeley Lab, HRIBF, Yale, Texas A&M, and other institutions have higher-energy, stable-beam machines that can probe details of nuclear structure important for astrophysical problems. ORELA and the SNS at Oak Ridge and LANSCE at Los Alamos will provide neutrons needed to understand the synthesis of heavy elements in red giants and in stellar explosions.

In the longer term, the Rare Isotope Accelerator (RIA) will be needed to forge real progress in several important areas. RIA will deliver a wide range of radioactive beams and will thus provide the tools for establishing a firm empirical basis for new knowledge of the origin, assembly, and interactions of nuclear matter far from stability. Such knowledge is needed, for example, to expand what is known of stellar explosions. Along with other technological developments (for example, large detector arrays), RIA has the potential to launch a new golden era of nuclear astrophysics to rival that of observational astrophysics, to which it is intimately linked.

The following sections illustrate the breadth of astrophysical phenomena in which nuclear physics plays an important role, summarize recent progress and open questions, and describe the resources needed to tackle these cosmic puzzles.

Going Out with a Bang: Supernovae Explosions

Core-collapse supernovae are extraordinary cosmic events, signaling both a dramatic end to the life cycle of massive stars and the birth of neutron stars and black holes. They are among the most energetic explosions in the universe, with the final stages shredding, in less than a second, a star that took hundreds of millions of years to evolve. They radiate 10^{51} ergs of energy in the optical band and 100 times that in elusive neutrinos. Supernovae are the principal factories of new elements: They enrich our galaxy with nuclei near iron during the explosion; they eject the ashes of stellar burning, comprising carbon, oxygen, neon, and other elements, into the interstellar medium; and they possibly synthesize a large fraction of the heaviest elements by means of the rapid neutron-capture process (r-process). And finally, supernovae are also important laboratories for modern physics, testing what is known of hydrodynamics, general relativity, neutrino physics, and a great deal of nuclear physics. Thus, understanding the mechanism of core-collapse supernovae is of central importance, in astrophysics as well as in many other areas of physics.

Neutrinos and the supernova explosion mechanism. Advanced observatories are now making detailed observations of about 20 supernovae each year, and yet, despite tremendous theoretical and experimental efforts, stars cannot yet be made to explode in the best computer simulations. Current assumptions hold that the explosion is initiated when a star with a mass of 8–30 times that of the sun has exhausted its nuclear fuel, and thermonuclear burning can no longer prevent gravitational collapse of the core. After compression to densities greater than that of nuclear matter and subsequent heating to high temperatures, the central core rebounds, giving rise to a shock wave that begins to propagate out of the core while the outer layers are still falling in. Much of the shock energy is, however, lost to dissociating the heavy nuclei in the core, causing the shock wave to stall. The hot core is, however, cooling by the emission of an intense flux of neutrinos, in effect acting like a neutrino light bulb radiating 10^{50} watts of power. The interaction of the neutrinos with the high-density stellar material may revive the shock wave, causing it to move out and shred the star, blowing the outer layers into the interstellar medium and leaving behind a neutron star or a black hole as the explosion remnant.

We have made significant progress in modeling this process by using laboratory nuclear physics results, coupled with hydrodynamics simulations (see Figure 2.16). For example, more accurate neutrino transport is now being utilized in one-dimensional (spherically symmetric) models. Recent progress has also been made in calculating electron-capture rates crucial to understanding the collapse of the core. These calculations differ substantially from earlier estimates, and radioactive-beam experiments are needed to test the new predictions of electron-capture rates on unstable nuclei. Furthermore, multidimensional models are now able to explore effects such as the convection induced by neutrino heating. These latter, more realistic models hold the key to the future. However, in spite of these advances, the detailed nature of the supernova mechanism still eludes description. There is hope that explosions can be simulated in multidimensional models that fully treat the microphysics (such as accurate neutrino transport). But this hope remains to be realized because of limitations on manpower and computational resources.

It is quite possible, however, that the current simulations omit some essential microphysics, such as detailed features of nucleon-nucleon, neutrino-nucleon, and neutrino-nucleus interactions, or changes in how opaque the stellar material is to neutrinos. Efforts to include such features require experimental investigations. For example, all but one of the rates for interactions between neutrinos and nuclei remain unmeasured. A facility enabling neutrino-nucleus cross-section measurements is needed to provide an experimental basis for this important information. Furthermore, since neutrinos play such an important role in the explosion, the

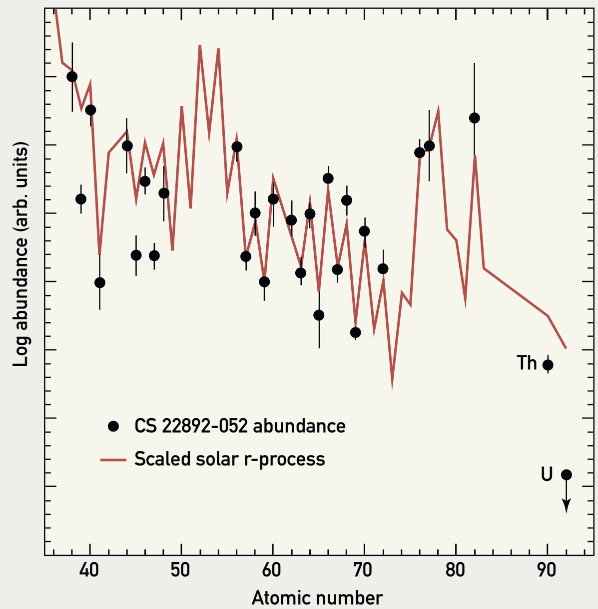
The Age of the Galaxy

We believe that the universe began in a hot, dense Big Bang about 10–15 billion years ago. Galaxies such as our Milky Way could have started to form within the first billion years after that, but the sun and the solar system are relative newcomers, appearing only 4.6 billion years ago. One of the challenges of modern cosmology is to link the conditions characterizing the early universe with what is observed today, and an important piece of the puzzle is the age of the universe. This can be estimated directly by several means, including measurements of the Hubble constant and observations of clusters of stars. The Hubble constant relates the distance of an object to its recessional velocity and thus offers a handle on the expansion rate of the universe. Taken together, these approaches yield ages in the range cited above. However, nuclear physics offers another means of determining the age of the Milky Way, with the promise of higher accuracy.

About half of the elements heavier than iron are synthesized in a sequence of rapid neutron captures and beta decays known as the r-process. Although the site of the r-process is unknown, extreme temperatures and densities make supernovae the most likely candidates. Because the stars that explode as supernovae are short-lived, determining when the r-process first occurred in our galaxy would provide a very good measure of its age.

It is now possible to make accurate measurements of the abundances of r-process elements in the atmospheres of very old stars. The pattern generally follows the known solar system abundance distribution; however, the relative abundances of thorium and uranium are observed to be significantly lower than in the solar system, a consequence of the radioactive decay of ^{232}Th and ^{238}U during the time since their synthesis. Using the radioactive decay law, and with model predictions for the production of ^{232}Th and ^{238}U, it is possible to place the age of our galaxy at 10–16 billion years.

To fully exploit this technique, however—and to sharpen this estimate further—it will be necessary to replace assumptions about the nature of the r-process with firmer insights. Understanding the details of the r-process and the conditions that give rise to the observed abundance distribution will require further work devoted to the structure of very neutron-rich nuclei. On the experimental front, RIA will make significant progress possible, whereas continued theoretical work is needed on the supernova mechanism itself, particularly in the areas of neutrino interactions and hydrodynamics. This work may eventually yield an age estimate with a precision of two billion years or less.



Signs of old age. The abundances of r-process elements on the surface of an old star (solid circles) and in the solar system (solid line). The lower stellar abundances of thorium and uranium reflect radioactive decay in the interval between the formation of the old star and the formation of the solar system.
From C. Sneden et al., Astrophys. J. 533, L139 (2000).

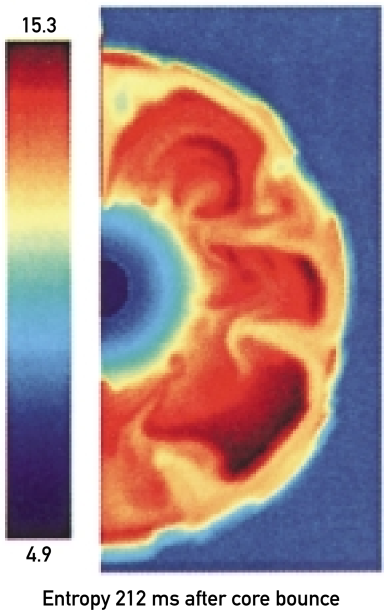


Figure 2.16. Modeling a cataclysm. A two-dimensional simulation of a supernova explosion shows the presence of large-scale motions of material—convection—in the inner core. Areas of high entropy are shown in red, low entropy in blue. Along with the interactions of neutrinos with nuclei, convection may play an important role in reenergizing the stalled outward-traveling shock wave in these explosions. *Image courtesy of A. Mezzacappa, Oak Ridge.*

construction of underground laboratories to detect neutrinos from a supernova burst in our own galaxy could enable a breakthrough in supernova modeling. Further work is also needed on the equation of state for dense nuclear matter and on the role of convection, rotation, and general relativity in the explosions.

Heavy-element factories: Supernova nucleosynthesis. Core-collapse supernovae remain the most promising site for r-process nucleosynthesis—a sequence of rapid neutron captures on neutron-rich unstable nuclei, interspersed with beta decays—which is the process believed to form roughly half of the elements heavier than iron (see Figure 2.17 and "The Age of the Galaxy," page 58). While stars process hydrogen and helium fuel into medium-mass elements over hundreds of millions of years, supernovae process some of this into heavier elements in just a few seconds and then disperse almost all of it into space to seed future generations of stars and planets. For these reasons, supernovae are referred to as heavy-element factories. Recently, astronomers have directly observed the elemental abundances on the surfaces of very old, metal-poor stars in the halo of our galaxy. The results reveal a distinct r-process signature.

Current supernova models suggest the presence of conditions necessary for the r-process in the wind from the surface of newly born neutron stars. Specifically, in this region there are thought to be very high neutron densities (~10^{20} neutrons cm^{-3}) and temperatures (>10^9 K), and heavy "seed" nuclei with masses of 60–100, formed via the assembly of nucleons and alpha particles. While the conditions for an r-process may exist, more work needs to be done to determine if the r-process actually occurs in supernovae.

Unraveling the mystery of the r-process requires an understanding of neutron-rich unstable nuclei. At the temperatures and densities in supernovae, the neutron-capture reactions are so fast (on the order of seconds) that the nucle-

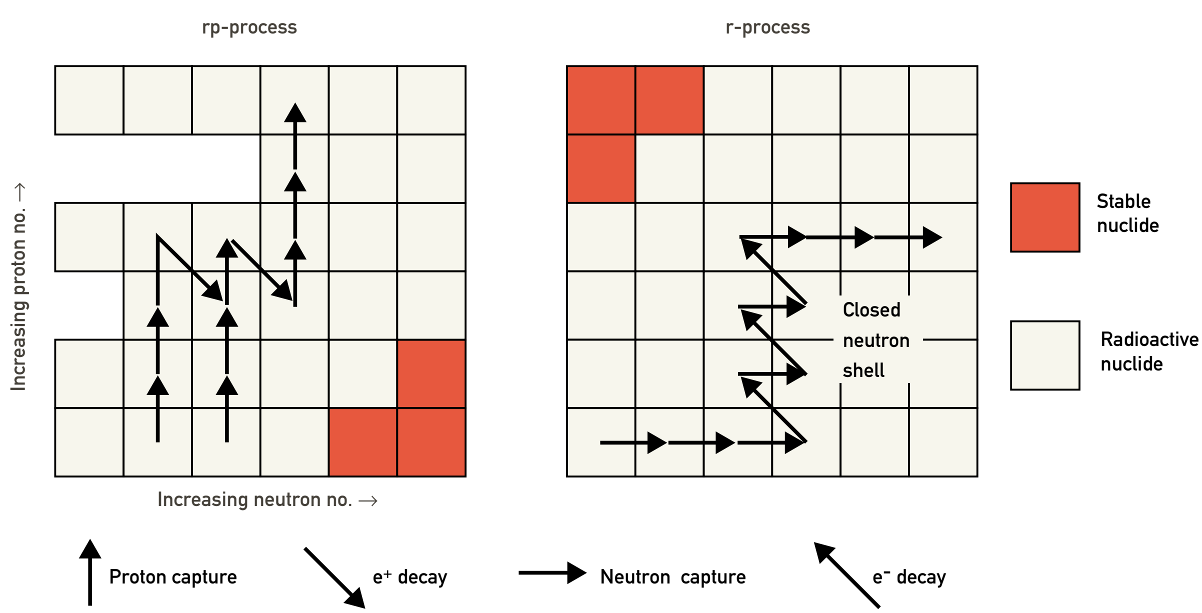


Figure 2.17. Recipes for new elements. The two diagrams illustrate representative stellar nucleosynthesis reactions as they might occur in the rp-process (left) and the r-process (right). The regions in which these processes occur are illustrated schematically in Figure 2.11.

osynthesis initially depends primarily on the nuclear structure properties of more than 1000 neutron-rich unstable nuclei. The required information includes masses, neutron separation energies, beta-decay lifetimes, beta-delayed neutron-decay probabilities, and level densities. Global nuclear structure models are therefore crucial, and measurements are absolutely necessary to benchmark these calculations. The weak binding inherent in nuclei at the drip lines gives them nuclear properties profoundly different from those of nuclei near stability. The underlying shell structure, which responds to the presence of weakly bound states and of diffuse matter, may be strongly affected. Recent calculations indicate that a quenched neutron shell structure with dramatically reduced shell gaps, possibly reordered orbitals, and new magic numbers may occur near the neutron drip line. These can all have astrophysical implications: Recent calculations of r-process nucleosynthesis using ad hoc quenching of shell gaps significantly change the prediction of heavy nuclei abundances synthesized in the explosion, as compared with predictions using a traditional shell model out to the drip line.

In addition to the nuclear structure information, the capture rates are important, especially for determining the reaction path at the lower temperatures toward the end of the r-process. Because the relevant nuclides lie so far from the valley of stability, no reactions along the r-process path have yet been measured directly in the laboratory. One approach may be to study (*d,p*) transfer reactions in inverse kinematics with nuclei on or near the r-process path. The aim would be to obtain the level information and spectroscopic factors of single-particle states needed to determine neutron-capture reaction rates. Other transfer reactions may be useful in determining the direct-capture contribution to the reaction rate. A complementary approach would be to directly measure capture on unstable isotopes as far from stability as possible, with radioactive targets and an intense neutron source. Finally, recent calculations suggest that reactions on low-mass, neutron-rich nuclides may also affect the r-process, but more experimental information is needed to investigate this possibility.

Glowing embers in space: Long-lived radionuclides. Our galaxy glows with gamma radiation emitted from radioactive nuclei (for example, ^{44}Ti, ^{56}Co, and ^{56}Ni) in the ashes of stellar explosions. In fact, the decay of some of these nuclei powers the late-time light output of supernovae. Simulations suggest that they are synthesized in the region of the collapsing core and are thus components of the innermost material ejected into the interstellar medium (see "Galactic Radioactivity," page 62). Minor changes in supernova models can dramatically alter the predicted amounts of ejected radionuclides. Accordingly, these nuclei can serve as a powerful diagnostic of the supernova explosion mechanism. It is, therefore, important to understand the nuclear reactions that create and destroy these long-lived radionuclides, as those reactions dictate the quantities of ejected nuclei, as well as the resulting observable gamma-ray flux.

Supernovae may also be responsible for the origin of the rare p-nuclides via a series of photodissociation reactions (the p-process). We have little experimental information on the p-process, and measurements are needed to improve the statistical model calculations of p-process reaction rates. In addition, supernova nucleosynthesis may also be modified by the interactions of neutrinos with the stellar material, an effect we are just starting to examine and for which no relevant experimental neutrino-nucleus data exist. Neutrino processes may produce significant amounts of rare nuclides such as ^{180}Ta, as well as fragile nuclides such as ^{19}F. Verification of such possibilities will require measurements of neutrino-nucleus cross sections as described above. Subsequent realistic inclusion of these processes in supernova simulations may improve the agreement between theory and observations.

The largest nuclei: Neutron stars. Neutron stars, formed as remnants of supernovae, are among the most unusual objects in the universe. They contain a mass equal to that of the sun in a sphere with a radius of 10 km. The densities range from 0.002 to 10 times that of nuclei—up to ~10^{15} g cm^{-3}. Many neutron stars form pulsars, emitting radio waves that appear from the Earth to pulse on and off like a lighthouse beacon as the star rotates at very high speeds, up to 1000 revolutions per second. Other neutron stars accrete material from a binary companion star and flare to life with a burst of x-rays (see below). These explosions are driven by nuclear reactions on proton-rich radioactive isotopes and are discussed in more detail below. A wealth of observational data has been collected on neutron stars: their rotational period, estimates of their mass, and their x-ray flare-ups. Efforts to understand the nature of these objects involve nuclear physics, general relativity, particle physics, and astrophysics. The pertinent nuclear physics questions concern the nature of dense nuclear matter in which two- and three-nucleon interaction potentials play a key role; theoretical calculations and measurements at intermediate-energy facilities will be crucial here. Additionally, mixed phases of nuclear and quark matter are thought to exist in these stars, a state of matter that is particularly challenging to understand.

Supernovae and RIA. Because we will never measure the properties of all the relevant nuclides and their capture cross sections, it is crucial to utilize measurements on a number of key nuclides to refine global model predictions for nuclei involved in the r-process and for their interactions. Operating radioactive-beam facilities will enable the first study of structure and reactions of neutron-rich nuclei in the r-process path, and significant progress in this area can be expected in the next few years at NSCL and HRIBF. However, these facilities provide access to only a limited number of the pertinent nuclei. RIA will be the world's only facility to provide the plethora of beams and the needed intensities for r-process studies. With RIA, nearly all of the r-process path will be experimentally accessible, and a firm experimental basis for understanding r-process nucleosynthesis will be within reach.

Stellar Cannibals: Explosions in Binary Systems

Another class of explosions arises from cannibalistic acts between stars. More than half of all stars occur in binary pairs, and it is not uncommon for some stellar material to be transferred from one star to the other as the pair evolves. However, in some cases, this mass transfer can produce violent thermonuclear explosions—novae and x-ray bursts—in which the more highly evolved star (a cold, dark cinder such as a white dwarf or a neutron star) can briefly flare back to life. These are not rare events: We can observe approximately 40 nova explosions in our galaxy each year. These thermonuclear explosions are driven by nuclear reactions on radioactive nuclei and are characterized by very high temperatures and densities and by large amounts of hydrogen and helium. Under such conditions, proton- and alpha-induced reactions proceed so quickly that any proton-rich radioactive nuclei formed can undergo further reactions before decaying back toward stability. Fundamentally different sequences of nuclear reactions therefore occur in stellar explosions, compared with those in stars in hydrostatic equilibrium.

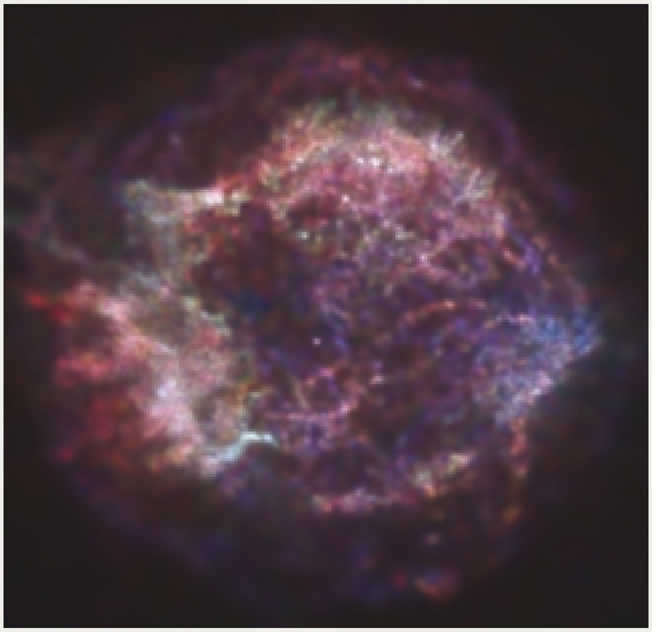
Even though a wealth of new observational data is now available on novae and x-ray bursts, we still lack the nuclear physics information we need to understand the underlying explosion mechanism. This is likewise true for the explosive burning of proton-rich unstable nuclei that is involved in other, more exotic astrophysical phenomena, such as the enormous disks of stellar material that can accrete around black holes, or the so-called supermassive stars. The latter are thought to have masses 10^5 times the mass of the sun and to ultimately collapse into supermassive black holes. These stars may therefore be the precursors of the supermassive black holes that are the engines of active galactic nuclei and that seem to reside at the centers of many galaxies, including our own. The nuclear physics of unstable isotopes plays a key role in all of these phenomena.

The case of the missing mass: Nova explosions. Nova explosions occur when a bloated star transfers matter to a white dwarf companion star, initiating a violent runaway thermonuclear explosion, with an energy release of 10^{38}–10^{45} ergs in less than 10^3 seconds. Novae represent promising "laboratories" for the study of convection, a poorly understood but crucial part of stellar astrophysics. This is because the nova mechanism relies on mixing within a fairly well-defined shell of material, and, unlike examples of nonexplosive stellar mixing, the results are directly observable in the outburst, with little modification.

Temperatures and densities greater than 10^8 K and 10^3 g cm^{-3}, respectively, can be reached during a nova explosion, causing nuclear reactions on proton-rich radioactive nuclei to generate energy up to 100 times faster than reactions on stable nuclei. It is this energy release that characterizes the nova phenomenon. The thermonuclear burning in the hot CNO cycle and in the rapid proton-capture process (rp-process) synthesizes nuclides up to mass 40 with an abundance pattern very different from that produced in quiescent stars (see Figure 2.17). Novae are the principal sources of certain light nuclei (for example, ^{13}C, ^{15}N, and ^{17}O), and they may also synthesize gamma-ray-emitting radioactive nuclei in observable quantities. Based on current nova models, devices such as INTEGRAL and the Advanced Compton Telescope are expected to have the sensitivity to detect gamma-ray lines from the decay of nuclei such as ^{18}F, ^{22}Na, and ^{26}Al. Since the production rates for these nuclei are strongly dependent on the temperatures, densities, and mixing that occur in the explosion, the measured gamma-ray intensities can, in principle, provide a valuable diagnostic of the nova mechanism. Currently, however, uncertainties in nuclear reactions with radioactive nuclei limit the accuracy of

Galactic Radioactivity

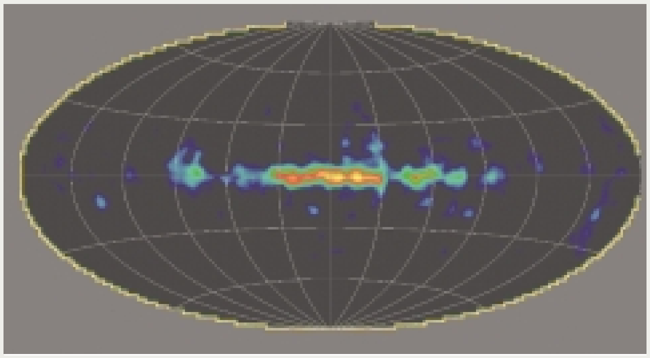
The abundances of the elements in the interstellar medium (ISM) record the history of stellar evolution in the galaxy. Radioactive nuclei can be a particularly useful means of interpreting this record, because they carry temporal information and can often be associated with a particular production site. For example, the decay of ^{56}Co ($t_{1/2}$ = 77 days) produced by Supernova 1987A has been detected by the COMPTEL telescope on the orbiting Compton Gamma Ray Observatory. This observation revealed that a mass of ^{56}Ni equal to about 7.5% of the mass of the sun was ejected into the ISM. In addition, the remnant of an older supernova, Cas A, shows the characteristic signature of ^{44}Ti ($t_{1/2}$ = 60 years). These results can be used to determine how much material was ejected into the ISM by this latter explosion, as well as the conditions near the collapsing core.



Remnants of Cas A. Supernova explosions such as this, which is 10,000 light-years distant, contain the elements that make up people and planets. This Chandra X-ray Observatory image of the supernova remnant Cassiopeia A shows in unprecedented detail where the intensities of low-, medium-, and high-energy x-rays are greatest (red, green, and blue, respectively). The red material on the left outer edge is enriched in iron, whereas the bright greenish white region on the lower left is enriched in silicon and sulfur. In the blue region on the right edge, low- and medium-energy x-rays have been filtered out by a cloud of dust and gas in the remnant. The iron-rich features synthesized deepest in the star are near the outer edge of the remnant, surprisingly suggesting that the explosion turned the star completely inside out. *Image courtesy of NASA/CXC/SAO.*

A number of instruments have detected gamma rays from the decay of ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ years). In this case, as illustrated below, the emission is spread throughout the galactic plane, and for this reason, it has been difficult to associate the production of ^{26}Al with any one site. The lumpiness of the distribution does suggest that production is episodic, which would be expected if massive stars were the dominant source. We also see clear evidence, in the form of anomalous enhancements of ^{26}Mg in meteoritic grains, that ^{26}Al was present in the early solar system. Interestingly, the early solar system had an ^{26}Al/^{27}Al ratio that was 10 times the norm for the present ISM. These last two discoveries could provide answers to questions regarding the astrophysical sources of ^{26}Al in the galaxy, and the circumstances and conditions at the time of the solar system's birth.

Interpreting these observations requires calculations of nucleosynthesis from a variety of sources, which in turn utilize nuclear input, such as reaction rates and half-lives. New gamma-ray observatories, such as INTEGRAL and GLAST, will offer unprecedented spectral resolution and sensitivity. The information provided by these new missions will answer some outstanding questions in nucleosynthesis, while at the same time raising new ones that will motivate future work in nuclear astrophysics.



Aluminum in the galaxy. A detailed map made by COMPTEL shows the intensity of 1.8-MeV gamma-ray lines in our galaxy. These photons correspond to the radioactive decay of ^{26}Al into ^{26}Mg. The relatively short (7.2×10^5 years) half-life of this decay (compared to the galactic age of billions of years) means that the ^{26}Al was synthesized by nuclear reactions relatively recently. *From S. Plüschke et al., AIP Conf. Proc. 510, 35 (2000).*

such an analysis. As a consequence, measurements of the rates of key reactions using unstable beams will be crucial for interpreting the gamma-ray measurements.

X-ray bursts. Explosions in binary star systems containing a neutron star—x-ray bursts and x-ray pulsars—reach even higher temperatures and densities than novae: over 10^9 K and 10^6 g cm^{-3}, respectively. The ensuing hydrogen burning may synthesize proton-rich nuclides with masses of 80–100 and higher. X-ray bursts occur at low mass-transfer rates and feature 10- to 100-second-long pulses of nuclear burning that repeat with a period of hours or days. By contrast, x-ray pulsars occur at high mass-transfer rates with steady-state nuclear burning. Both astrophysical scenarios are driven by nuclear reactions on proton-rich radioactive nuclei. We need the rates of these reactions to explain explosion observables, such as the x-ray luminosity as a function of time, and to determine the production of some heavy nuclides (for example, ^{92}Mo and ^{96}Ru), which are difficult to produce in other astrophysical environments. Furthermore, the ashes of the burning settle onto the neutron star and alter its composition, and can thereby influence the emission of potentially detectable gravitational waves from the rapidly spinning neutron star.

Other nuclear processes that come into play in the crust of the neutron star are electron captures, as well as pycnonuclear reactions, where fusion is induced by high densities rather than high temperatures. These involve neutron-rich nuclei out to the neutron drip line, which have never been studied. Also needed are nuclear structure studies (masses, lifetimes, beta-delayed particle emission, and level structure) near the proton drip line. Special attention is needed to nuclei with equal neutron and proton numbers that are so-called waiting points; examples include ^{64}Ge and ^{72}Kr, where the reaction flow slows unless two-proton-capture reactions provide a bypass. Recent simulations suggest that these explosions can synthesize material up to the Sn–Te region, but not beyond; nuclear structure experiments on, for example, the proton separation energies of antimony isotopes are needed to verify this as the endpoint of x-ray burst nucleosynthesis.

Standard candles and dark energy: Type Ia supernovae. If the mass transfer from one star to another in a binary pair is high enough, a Type Ia supernova can result. Nuclear burning of the transferred hydrogen to carbon and oxygen adds to the mass of the white dwarf, causing a gravitational contraction when the mass exceeds 1.4 times that of the sun. This ignites a thermonuclear runaway via carbon burning at the center of the white dwarf, causing the complete disruption of the star (with no remnant) and the output of an enormous amount of energy. The extreme brightness that results —and our ability to predict this brightness—makes these supernova explosions very useful as indicators of cosmological distances and, accordingly, the expansion rate of the universe. These explosions have thus been dubbed "standard candles."

Type Ia supernovae were recently used to determine that the expansion rate of the universe is increasing, implying the existence of a nonzero cosmological constant or "dark energy." The use of Type Ia explosions as standard candles in cosmology does, however, depend on our ability to calculate their luminosities, and this depends on nuclear physics—such as the important ^{12}C$(\alpha,\gamma)^{16}$O reaction, as well as electron captures on iron-group nuclei and neutron-rich nuclei with $Z < 40$. More work is needed to place our understanding of this nuclear physics on a firmer empirical foundation.

Experimental underpinnings of binary explosions. The recent availability of beams of radioactive nuclei has enabled the first measurements of a few important reactions and nuclear structure relevant to understanding nova and x-ray burst nucleosynthesis—and more progress is expected at facilities such as HRIBF and NSCL. Transfer reaction studies at stable-beam facilities are also important in this effort. The solution to some of the open questions mentioned above regarding binary explosions will, however, require a facility such as RIA. By providing unprecedented intensities of variable-energy, high-quality beams of proton-rich radioactive nuclei, RIA will enable direct measurements of the structure of proton-rich unstable nuclei and the reactions that drive explosions in binary systems. This, in turn, will enable breakthrough studies of these systems.

The Biggest Bang: Light Element Formation in the Early Universe

Nuclear physics provides an excellent window for us to view the early universe, as well as to study its current large-scale structure and future evolution. In standard Big Bang models, the universe at an age of approximately 100 seconds contains, in part, a homogeneous, hot (1 MeV), rapidly expanding gas of protons and neutrons. As the universe expands and cools, nuclear processing assembles almost all of the free neutrons into ^{4}He; tiny amounts of deuterium, tritium, ^{3}He, and ^{7}Li nuclei are also formed. The ^{1}H and ^{4}He formed in the first three minutes after the Big Bang are the raw materials for the stars that begin to form 10^4 years later.

The only free parameter in standard Big Bang nucleosynthesis models is the density of "normal" (baryonic) matter in the universe. There is a range of densities for which all of the light-element abundances predicted by Big Bang models agree with the "observations," namely, the primordial abundances inferred from present-day observations of metal-poor stars in the halo of our galaxy and from the absorption of light emissions from quasars by clouds of gas and dust in space. The constraint of this extremely important cosmological parameter to about 0.01–0.1 times the closure density of the universe is a great triumph of nuclear astrophysics, especially considering that light-element abundances range over a factor of a billion.

Recent measurements have focused on reducing the uncertainties in nuclear reaction rates, in an effort to define the baryonic density more narrowly, while theory has focused on detailing the influence of these rate uncertainties on primordial abundance predictions. More accurate measurements of some reactions, such as ^{3}He$(\alpha,\gamma)^7$Be, will help refine the predictions of the Big Bang models; these experiments require low-energy, high-current light-ion accelerators.

The Quiet Years: Hydrogen and Helium Burning

Stars evolve as a direct consequence of the nuclear reactions that occur in their interiors, and different phases in the lives of stars can be directly related to particular nuclear reaction sequences. For most of their lives, stars produce energy by means of the fusion of hydrogen into helium—"hydrogen burning." Since the essential features of hydrogen burning have been well understood for 40 years, this reaction is used as a tool to probe the structure and evolution of stars, including our sun, which are in the quiescent, "main sequence" stage of their life cycles.

The vast majority of stars, those with masses less than 1.5 times that of the sun, convert hydrogen into helium primarily via nuclear reactions in the *pp* chains. While most of these reactions are well understood, the rates of the ^{3}He$(\alpha,\gamma)^7$Be and ^{7}Be$(p,\gamma)^8$B capture reactions are still somewhat uncertain at solar energies. These reactions, while less important from the standpoint of stellar structure and evolution, are noteworthy because the decays of ^{7}Be and ^{8}B produce the high-energy solar neutrinos. Although it is now clear that neither reaction can account for the discrepancy between the predicted and measured fluxes of solar neutrinos (the "solar neutrino problem"), both play a role in the interpretation of results from solar neutrino detectors. For example, the uncertainty in the ^{7}Be$(p,\gamma)^8$B reaction rate makes the largest nuclear physics contribution to the uncertainties in the parameters of neutrino oscillation "solutions" to the solar neutrino problem. With SNO in operation and Borexino under construction, further studies of these reactions are both needed and timely.

Bloated stars: Red giant formation. Main sequence stars more massive than about 1.5 solar masses have hotter interiors than less-massive stars and produce energy via the CN cycle, in which carbon and nitrogen act as catalysts in the conversion of hydrogen into helium. The rate of energy generation is regulated by ^{14}N$(p,\gamma)^{15}$O, the slowest reaction. This burning occurs in the core and, after the core hydrogen is exhausted, in a thin shell surrounding the core. At this later stage, the intense luminosity of the shell causes the star's surface to expand, increasing the star's diameter by ten- to a hundredfold. The star becomes a red giant. Convection may now reach deeply enough to bring material that has undergone hydrogen burning to the surface, giving astronomers a first glimpse of the stellar interior and evidence of nuclear burning by the CN cycle.

At low energies, the mechanism behind the ^{14}N$(p,\gamma)^{15}$O reaction is complicated, and existing measurements are not sufficient to determine the stellar rate reliably. This uncertainty affects a variety of important topics in stellar structure and evolution, including the transition between the main sequence phase and the red giant phase, and the luminosity occurring in core helium burning. These further uncertainties, in turn, influence efforts to determine the ages, evolution, and distances of globular clusters. These enormous collections of commonly evolved stars are the frequent target of astrophysical observations, because they are among the oldest objects known in the galaxy (and hence can provide a galactic age) and because they can provide important tests for stellar evolution theory. More precise measurements of the behavior of the ^{14}N$(p,\gamma)^{15}$O reaction at very low energy are critical for studies of these issues.

Puzzles of hydrogen burning in red giants. Hydrogen burning in the core shells of red giants proceeds at higher temperatures than core burning, and consequently, nucleosynthesis can move beyond the CN cycle into the CNO, Ne-Na, and Mg-Al cycles. Although not major contributors to the stellar energy budget, these cycles produce nuclei such as neon and sodium isotopes and ^{26}Al, which have become important tools of stellar spectroscopy. Many open questions remain concerning the nuclear physics of hydrogen burning in red giants. For example, sizable uncertainties associated with reactions producing sodium within the Ne-Na cycle prevent a clear interpretation of observations of abundance anomalies on the surfaces of stars in globular clusters. Likewise, uncertainties in CNO and Ne-Na cycle reactions prevent the use of ^{17,18}O and ^{23}Na as tracers of stellar convection, the most poorly understood aspect of stellar models.

Furthermore, rate uncertainties in the Mg-Al cycle hamper a proper interpretation of the mapping by the Compton Gamma Ray Observatory of gamma rays from the decay of the long-lived radionuclide ^{26}Al across the galaxy (see page 62). Since the half-life of ^{26}Al ($t_{1/2} = 7.2 \times 10^5$ years) is short as compared with the time scale of galactic chemical evolution (~10^{10} years), this crucial observation is clear evidence that nucleosynthetic processes are currently active in the galaxy and are releasing 1–3 solar masses of ^{26}Al per 10^6 years into the interstellar medium. A wide variety of stellar sites have been suggested as sources of ^{26}Al, including massive Wolf-Rayet stars, core-collapse supernovae, nova outbursts, and red giants. Determining the actual source or sources will help solve puzzles in models of stellar evolution and illuminate the origin of our solar system, but this will require reducing the large uncertainties in the reaction rates in the Mg-Al cycle, involving both stable and radioactive magnesium, aluminum, and silicon isotopes.

Measurements of the small cross sections of hydrogen-burning reactions require dedicated, high-intensity (~mA), low-energy (<3 MV) accelerators, coupled with innovative detection systems such gamma-ray tracking detectors. These systems would permit measurements within the actual range of stellar energies, instead of relying on measurements at higher energies (with higher cross sections), which then require problematic extrapolations to the low energies of interest. Another possibility is to place an accelerator deep underground, where background events from cosmic rays would be greatly reduced.

Some reactions are simply too slow to be measured directly at relevant energies, though they can still be studied using a variety of indirect spectroscopic techniques. For example, measurements of proton-stripping reactions and Coulomb-dissociation techniques are used as alternative means to study (p,γ) reactions. In some cases, direct and indirect measurements can be combined to overcome the systematic limitations of one or both methods. A variety of low- and medium-energy facilities is essential for these important indirect studies. A combined approach of direct and indirect measurements will become more necessary as the interpretation of astrophysical observations continues to require increasing precision from nuclear physics.

Helium burning. When the contracting, helium-rich core of a red giant reaches sufficient density and temperature, helium burning begins by means of the well-understood triple-alpha process, the fusion of three ^{4}He nuclei to form ^{12}C. This new energy source stabilizes the core's contraction. This reaction and several other alpha-capture reactions (on, for example, ^{12}C, ^{14}N, ^{16}O, and ^{20}Ne) characterize the helium-burning phase of stellar evolution. Since alpha-capture reactions are typically harder to measure than proton-capture reactions (because of the increased Coulomb barrier and higher background levels), experimental data are sparse, and some very basic issues concerning helium burning still remain unresolved.

Many of these questions require a better determination of the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate. This reaction is of enormous significance for late stellar evolution: It helps to determine the mass of the core following helium burning, as well as to fix [together with the ^{16}O$(\alpha,\gamma)^{20}$Ne reaction] the C/O ratio, which in turn influences all later nuclear burning stages in a star. For these reasons, the experimental determination of the reaction rate for ^{12}C$(\alpha,\gamma)^{16}$O has been one of the important goals in nuclear astrophysics for the past three decades. The experimental situation has been improved by recent measurements with low-energy alpha particles and by measurements of the beta-delayed alpha decay of ^{16}N. However, the small cross section and the complexity of the reaction mechanism at low energies have severely handicapped attempts to reduce the uncertainty at stellar energies from the current factor of two to the needed level of 20%. More work is needed in this area, requiring high-intensity, low-energy stable-beam facilities.

Advanced Stages of Stellar Burning

For stars with masses greater than eight times that of the sun, exhaustion of the ^{4}He fuel in the core leads to further stages of evolution characterized by carbon, neon, oxygen, and silicon burning. These processes are driven by heavy-ion fusion and photodisintegration reactions, and they depend upon the fusion of ^{12}C and ^{16}O and upon subsequent alpha and proton captures on the fusion products. For example, nuclides such as ^{28}Si and ^{32}S are formed by the photodisintegration of ^{20}Ne (formed during carbon burning) to oxygen and subsequent oxygen-oxygen fusion reactions. Burning stages beyond oxygen burning are relevant for the synthesis of nuclei heavier than calcium in the pre-supernova phase of the star. At the highest temperatures, burning occurs in a state of full nuclear statistical equilibrium (NSE), where the abundances produced are governed by chemical potentials and thus depend only on the temperature, density, nuclear binding energies, and partition functions of the nuclei involved. This equilibrium breaks down for temperatures below about 3×10^{9} K, and at these lower temperatures, different nuclear mass regions can already equilibrate separately with the background of free neutrons, protons, and alphas. Such quasi-equilibrium (QSE) clusters are connected by slow reactions and have total abundances that are offset from the NSE values. Some individual reaction rates therefore remain important for element production in this burning and need to be determined experimentally. The study of the QSE clusters is a valuable tool in deciphering the behavior of nucleosynthesis processes at temperatures below those required for NSE.

Giant Red Fingerprints

In the red giant stardust model, nuclides synthesized via the s-process during the red giant phase of a star's life are mixed by convection in the cooler outer regions of the star. As the material cools, microscopic grains of refractory materials, such as silicon carbide, form and trap within them trace quantities of s-process isotopes, thus preserving the unique isotopic signature of the s-process environment in this star. Today, this stardust can be found as tiny grains in primitive meteorites.

In the past few years, it has become possible to measure the isotopic ratios of the trace elements in these grains, using ion microprobes and other techniques. Qualitatively, these measurements agree with s-process stellar models. For example, isotopes believed to be formed only in the s-process with no r-process contribution ("s-only" isotopes) were found to be relatively enriched, whereas p-only and r-only isotopes, as well as isotopes having contributions from both the s- and the r-process, were depleted. However, substantial *quantitative* differences remained between the model and the observations, though these differences were obscured by large uncertainties in the neutron-capture reaction rates.

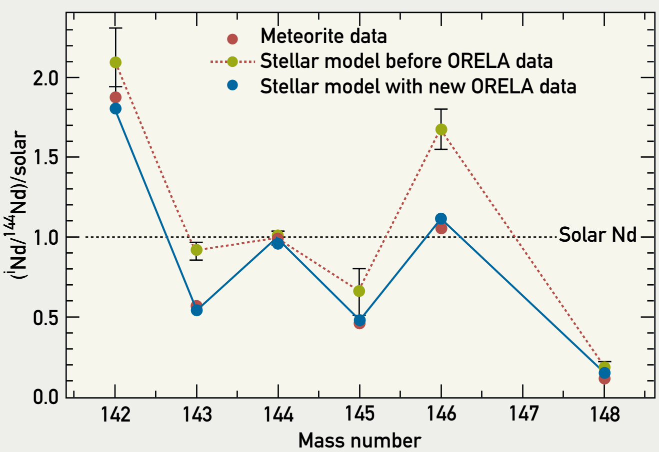
The first truly quantitative test of the red giant stardust model was made possible by recent high-precision neutron-capture measurements on isotopes of neodymium. These new data show that the old rates were seriously in error, and s-process stellar model calculations with the new rates have produced excellent agreement with the meteorite data, as shown on the far right.

Death of a giant. Red giant stars form nebulae such as the Cat's Eye Nebula as they die, as strong winds blow off the star's surface. Our own sun will do this in a few billion years. Material coalescing in such nebulae may reach the Earth in the form of meteorites.

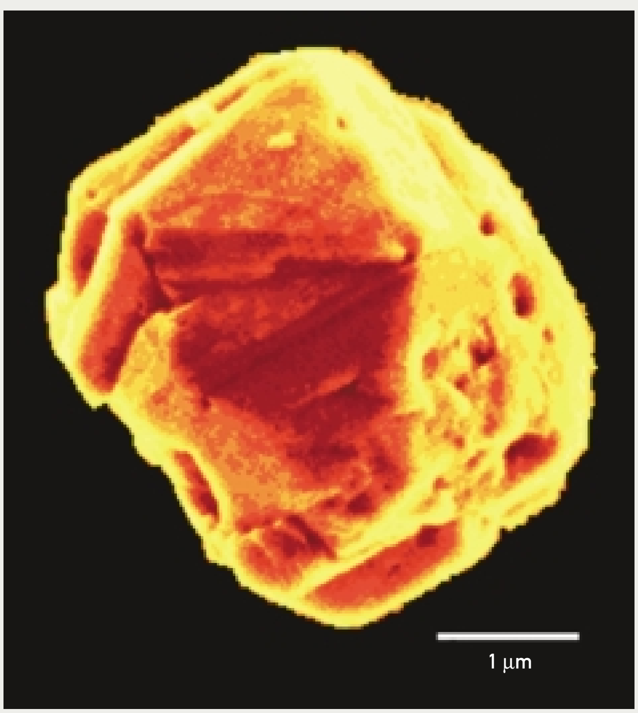
Slow cooking of heavy elements. About half of the elements heavier than iron are formed in the slow neutron-capture process (s-process), which occurs during the helium-burning phase of a star's life. Heavy elements are built by a sequence of neutron captures and beta decays, which mainly process material from seed nuclei located below and near the iron peak into a wide range of nuclei extending up to lead and bismuth. In contrast to the r-process, the neutron-capture times are usually longer than the competing beta-decay half-lives, and thus the s-process path runs along the valley of stability in the nuclear chart. This means that the relevant neutron-capture cross sections and half-lives are much more accessible to experimental investigation, making the s-process the best-understood phase of nucleosynthesis. A recent success of s-process studies was the first quantitative confirmation of the theory that tiny grains in some meteorites carry a signature of abundances identical to that predicted in red giants and therefore originated in this astrophysical environment (see "Giant Red Fingerprints," below).

It is postulated that two s-process components are needed to reproduce the observed abundances. Helium flashes associated with rapid hydrogen mixing into the helium-burning carbon-enriched region are believed to be the site of the main s-process component that builds up the elements as heavy as lead and bismuth, with the $^{13}C(\alpha,n)^{16}O$ reaction being the main neutron source. The $^{22}Ne(\alpha,n)^{25}Mg$ reaction, which occurs during helium core burning of CNO material, is believed to supply the neutrons for the weak component that produces the nuclides with up to mass 90. Both the nature and the extent of convective processes,

On the other hand, still more-recent high-precision measurements on isotopes of barium and strontium have revealed puzzling discrepancies between the predictions of the red giant stardust model and the meteorite data. More precise neutron-capture measurements on other isotopes are needed to keep pace with the quickly growing body of precise isotopic abundance data for trace elements in meteoric grains, most of which appear to be due to the s-process.



From uncertainty to confirmation. Detailed analyses of small grains in meteorites show neodymium abundances that differ markedly from solar abundances. Stellar models based on old neutron-capture data failed to confirm that these grains carried a signature of red giant nucleosynthesis, but new precision measurements now provide a quantitative verification that these grains originated in red giants.



Interstellar grit. This ion microprobe image shows a SiC grain from a meteorite. Such grains contain elemental abundances that reflect their origins in red giants. *Image courtesy of S. Amari, Washington University.*

as well as the low-energy reaction cross sections for $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, are largely unknown and are treated as free parameters in present stellar modeling approaches. Determinations of these reaction rates are necessary ingredients in improved (and more realistic) models of these stars, especially models that treat convection and other mixing self-consistently.

The need for precision. Experimental uncertainties need to be reduced for many of the neutron-capture reactions that drive the nucleosynthesis of the heavy elements in red giants. Over the past 10 years, we have seen impressive improvements in the measurements of some important rates, and some are now known to the level of accuracy (1–3%) needed to test realistic stellar models and to make good use of the highly precise isotopic abundance measurements available from meteoritic stardust grains. Nonetheless, more high-precision measurements are needed, especially for the s-only isotopes (those produced solely by the s-process), for isotopes measured in stardust grains, and for isotopes with small cross sections. Also, neutron-capture measurements are needed for radioactive isotopes that are branching points in the s-process flow (where the rates for neutron capture and beta decay are similar). Analysis of these branching points can provide a direct handle on the "dynamics" of the stellar environment, such as the time dependence of the temperature, neutron flux, and matter density, as well as better information on the mean stellar environment.

The advent of high-flux neutron spallation sources will make measurements on important branching-point isotopes possible. New neutron-capture measurements are also needed at lower energies, because the latest, most successful stellar models indicate that the temperature during most of the neutron exposure in the s-process is much lower (kT = 8 keV) than previously thought (kT = 30 keV). Many of the older data do not extend to low enough energies to accurately determine the rates at this lower temperature, and rate extrapolations from higher temperatures are unreliable. It is also important to calibrate the effect of the population of low-lying excited states on neutron-capture rates, owing to the finite temperature of the s-process environment. Nuclear models indicate that this is most important in the rare-earth region, where the effects can be as large as 15%, but there are substantial differences among the predictions of different models. These effects can be determined by means of a series of neutron inelastic scattering experiments. To make all of these high-priority measurements will require complementary high-flux, low-resolution and lower-flux, high-resolution neutron sources, as well as the fabrication of radioactive targets, the availability of isotopically separated stable samples, and new high-efficiency, low-background gamma-ray detector arrays.

Outlook

As early as a half-century ago, a small number of seminal papers defined the field of nuclear astrophysics. On the basis of this early work, we have qualitative answers to some very deep questions about the origins of nuclei. For instance, it was clear then that the light elements arose from nuclear reactions that took place soon after the Big Bang. Today, this is still a cornerstone of Big Bang cosmology, along with the expansion of the universe and blackbody radiation. It was also apparent early on that at least two mechanisms (one rapid and one slow) contribute to the formation of the heavy elements and that several different astronomical sites must be involved in nucleosynthesis.

These key insights have been remarkably robust, but quantitative models have had mixed success in describing exactly what is going on and where it is happening. For example, the basic reactions in the burning of main sequence stars are rather well understood, but there are still significant qualitative, as well as quantitative, uncertainties about stellar explosions—for example, the site of the r-process is still unknown. Progress in understanding both nonexplosive and explosive environments will require a combination of advances in both experimental and theoretical nuclear physics. This work needs to be closely coupled to more elaborate studies to determine which nuclear physics information has the largest impact on astrophysical environments. Such sensitivity studies have, to date, shown that some of the most important information invariably requires pushing our current capabilities to the next level.

In the coming decade, a number of factors will combine to allow real progress on many fronts. First-generation radioactive-beam facilities will provide exceptional opportunities, as will selected experiments at stable-beam facilities. These have been described in some detail earlier in this section. It should be reemphasized here, however, that almost every one of these measurements, whether it uses a stable or an unstable beam, will test the limits of beam intensity and background level. These experiments will put great pressure on the facilities to improve productivity and increase beam time. For this reason, progress in nuclear astrophysics will benefit particularly from successful implementation of the *Facilities Initiative.*

Facilities such as NSCL and HRIBF, and later RIA, will provide new experimental input for r-process nucleosynthesis models. However, if we assume that supernovae are the sites for the r-process, nuclear physics can address only one part of the problem. Understanding a supernova explosion is a multidisciplinary physics challenge that will require a coordinated theoretical approach for its solution. Addressing this problem is a key focus of the *Nuclear Theory Initiative.* Simulating the explosion numerically is a key driver for the *Large-Scale Computing Initiative.*

We have known for some decades that successful modeling of a supernova explosion, and of the nucleosynthesis that takes place during it, would require knowledge of the nuclear equation of state, as well as detailed knowledge of the properties of very neutron-rich nuclei. Only in the past decade, however, has the importance of neutrino transport come to be fully appreciated. This too needs experimental input, and the proposal to build *ORLaND,* a dedicated facility to measure neutrino-nucleus cross sections represents an important opportunity.

As mentioned above, the measurement of nuclear reactions at astrophysically relevant energies is challenging for many reasons. It has recently been demonstrated that some of the background problems can be overcome by carrying out the experiments deep underground. The proposal for a *National Underground Science Laboratory* offers an outstanding opportunity to operate a high-current, low-energy accelerator in a laboratory setting with a low background level.

Another area of progress will be in precision measurements of isotopic abundances themselves. Beautiful results have been obtained for micrometeorites that originate outside the solar system, and further advances are expected both in these measurements and in astrophysical abundance observations. But the interpretation of these measurements relies heavily on very careful laboratory measurements of charged-particle and neutron-induced reaction cross sections.

Finally, for the long term, the *Rare Isotope Accelerator* will provide several orders of magnitude in increased sensitivity for measuring almost every nuclear parameter that requires an unstable beam or target. Which problems will have highest priority when RIA comes on-line will depend on the outcome of measurements during the coming decade at the first-generation radioactive-beam facilities. What cannot be disputed is that experiments at the limits of current technology will become routine at RIA, and others that are unthinkable today will be attempted.

In Search of the New Standard Model

Overview: Old Physics, New Physics

The search for a single framework describing all known forces of nature has been something of a Holy Grail in physics. Accordingly, one of the triumphs of late 20th century physics has been the establishment—and experimental confirmation—of such a framework for three of the four fundamental interactions: the electromagnetic, weak, and strong forces. The Standard Model of electroweak and strong interactions has by now been tested with impressive precision (~0.1% for electroweak phenomena) in tabletop experiments with atoms, in various nuclear experiments testing Standard Model symmetries, and in high-energy e^+e^- and $p\bar{p}$ annihilations.

Despite its successes, however, the Standard Model presents some conceptual difficulties, leading physicists to believe that it represents only a piece of a larger, more fundamental theory. For example, gravity remains to be fully incorporated into a framework including the other three forces, though the advent of string theory represents a breakthrough advance in this regard. In addition, the Standard Model itself contains 19 parameters whose origins and magnitudes are not explained by the theory but rather are taken from experiment. Indeed, the vast hierarchy of masses among the known elementary particles—ranging from neutrinos with masses no more than an eV/c^2 to heavy quarks near 10^{11} eV/c^2—is not explained by the Standard Model. Similarly, the Standard Model gives no reason for the quantization of electric charge, the weak interaction's flagrant disrespect for discrete symmetries (parity, P; charge conjugation, C; and time-reversal invariance, T), or the dynamics responsible for the predominance of matter over antimatter in the universe. Moreover, from a phenomenological standpoint, the recent observations of atmospheric neutrino oscillations by the SuperKamiokande collaboration—in tandem with data on solar and reactor neutrino oscillation searches—are not consistent with the Standard Model picture of three massless, purely left-handed neutrinos. Open questions such as these call for the development of a "new Standard Model," a model that builds on the successes of the current one while addressing its shortcomings.

Forty years ago, nuclear science played a crucial role in establishing the experimental foundations for the Standard Model. Precision tests of beta decay and muon decay demonstrated maximal parity violation, as well as important relationships between weak and electromagnetic interactions. Today, new experiments in nuclear physics and astrophysics may be uncovering the first hints of physics beyond the Standard Model. Especially significant recent accomplishments include:

- Observations of neutrinos using gallium detectors, which have shown that the number of low-energy electron neutrinos (those produced by weak interactions involving $p + p$ or ^{7}Be) reaching Earth from the sun is well below the number expected from the standard solar model. These results have confirmed and extended the pioneering experiments on solar neutrino detection that identified the solar neutrino problem.
- Measurements of the high-energy neutrino flux from the sun, which have demonstrated that the deficit of low-energy neutrinos on Earth is due to neutrino oscillations, implying that neutrinos have mass. This, together with the discovery of atmospheric neutrino oscillations, will require an extension to the Standard Model of fundamental interactions. This discovery also implies that neutrinos contribute at least as much mass to the universe as do the visible stars.
- A precision measurement of the magnetic moment of the muon, which has helped theorists discover an error in the Standard Model calculation and has placed important constraints on Standard Model extensions, such as supersymmetry.
- Dramatic improvements in experiments on nuclear electric dipole moments and double beta decay. These improvements place stringent bounds on violations of time-reversal symmetry and lepton number conservation.

While high-energy physicists typically search for "new physics" in large-scale experiments involving high-energy collisions of elementary particles, the avenue for nuclear physicists is through exquisitely precise measurements of various quantities. The presence—or even absence—of tiny deviations from Standard Model predictions for these measurements can provide important clues about the nature of the new theory. A number of current nuclear physics studies promise just such clues to the new Standard Model.

Symmetries and the Standard Model

Neutral weak phenomena. An early and stunning success of the Standard Model was the discovery of the Z^0 boson, whose existence and properties were predicted by the theory. The Z^0 mediates a component of the weak force in which the identities of all particles are preserved throughout the interaction. Such "neutral" weak interactions contrast with "charged" weak interactions, such as muon or nuclear beta decay, in which particle identities are transformed. In this sense, the neutral weak interaction is similar to the electromagnetic interaction—mediated by the photon—which also preserves particle identity. According to the Standard Model, the photon and the Z^0 are actually mixtures of primordial bosons, where the degree of mixing is described by a parameter θ_W, the weak mixing angle. Measurements of neutral weak phenomena are sensitive to $\sin^2 \theta_W$, and comparisons of $\sin^2 \theta_W$ extracted from a variety of different measurements have become an important means of testing the validity of the Standard Model.

To date, the most precise values of $\sin^2 \theta_W$ have been obtained in e^+e^- collisions at SLAC and CERN, where the center-of-mass energy in the collision is about 200 GeV. The Standard Model predicts, however, that the value of $\sin^2 \theta_W$ should vary from its high-energy value in processes at other energies. Two fixed-target experiments seek to test this energy dependence of $\sin^2 \theta_W$ for the first time with precision comparable to the high-energy determinations. Both experiments exploit the violation of parity invariance in the weak interaction to separate its effect from that of the electromagnetic interaction. Parity violation arises because neutral weak interactions between "left-handed" particles differ from those involving their mirror-image "right-handed" particles. (Parity symmetry states that any physical process will be identical to its mirror image. Thus, weak interactions do not respect parity symmetry.) Experimentally, this violation is isolated by comparing processes involving particles having opposite "handedness," such as polarized electrons. A measurement of the parity-violating asymmetry in polarized e^-e^- scattering is currently under way at SLAC, while an analogous measurement of the asymmetry for polarized e^-p scattering is under development for Jefferson Lab.

The Standard Model predicts that these asymmetries are roughly 10^{-7} or smaller, and useful extractions of $\sin^2 \theta_W$ require that experimental uncertainty be no larger than a few percent of this value. While measurements of this type are difficult, the results can have profound implications. Any observed deviations from the Standard Model prediction for the energy dependence of $\sin^2 \theta_W$ could signal the presence of new particles analogous to the Z^0 but as much as ten times heavier. Conversely, agreement with the Standard Model would tell us that mediators of the new Standard Model are considerably heavier than this.

An equally powerful probe of new physics involves the interaction between the photon and the magnetic moment of the muon. The Standard Model predicts that the muon's magnetic moment should differ from unity (in units of $e\hbar/m_\mu$) at the 10^{-3} level. The precision of this theoretical prediction is now at 0.6 ppm. Recently, the E821 collaboration at Brookhaven (see Figure 2.18) measured this so-called muon anomaly with a precision of 1.3 ppm and found a 2.6σ deviation from the Standard Model prediction—a deviation that prompted theorists to recheck their calculations. The subsequent correction of a sign error has now reduced the discrepancy to 1.5σ. As more than 80% of the data remain unanalyzed, the final result will provide a very stringent test of contributions from hypothesized "supersymmetric" partners of Standard Model particles. (The supersymmetric generalization of the Standard Model is a leading candidate for the new Standard Model.) While the magnetic moment of the electron has been measured with considerably better precision, the relatively larger mass of the muon makes its anomaly 40,000 times more sensitive to the presence of possible supersymmetric particles. In addition to particle physicists, cosmologists have a keen interest in the implications of this measurement, since one of the potential supersymmetric contributors to the muon anomaly—the neutralino—is also a favored candidate for dark matter.

Charged weak phenomena. Perhaps the most familiar process involving a charged weak interaction is the one responsible for the decay of ordinary matter: nuclear beta decay. The study of nuclear beta decay has played a key role in the development and testing of the Standard Model. Among the features of the Standard Model that follow from these studies are the violation of parity symmetry in charged weak interactions and the so-called conserved vector current, or CVC, relationships. Both of these features are reflected in the basic group theoretical structure of the

Standard Model. The CVC relationships, which have been confirmed to a few parts in 10^4 with nuclear beta decay (more specifically, the so-called superallowed Fermi beta decays have been used for this purpose), imply simple relations between charged weak interactions of light quarks and various light-quark electromagnetic properties. In addition, a comparison of nuclear beta decay with muon decay provides the most precise information about the way different flavors of quarks mix through the weak interaction. This mixing, which is also predicted by the Standard Model, implies that the "down"-type quark that participates in weak processes such as beta decay is not quite the same as the down quark that participates in strong interactions. In the Standard Model, this mixing is characterized by the CKM quark-mixing matrix, whose entries are determined from experiment. The most precisely measured of these entries is V_{ud}—the one governing beta decay, in which a down quark is transformed into an up quark (or vice versa). A comparison of V_{ud} with other entries in the quark-mixing matrix also provides important information about the possible structure of the new Standard Model.

Studies of nuclear beta decay have also been used to establish limits on the possible existence of right-handed charged weak interactions (which do not exist in the Standard Model) and an exotic class of effects known as second-class currents, whose presence is forbidden by the isospin symmetry of strong interactions among light quarks. In addition to studying nuclear and neutron beta decay, nuclear physicists are also making important contributions to the study of the weak decays of pions and muons. The results from these experiments also confirm the Standard Model predictions with a high degree of accuracy and, with the advent of improved experimental precision, are poised to uncover signatures of new physics at the TeV scale.

The study of superallowed nuclear beta decay, as well as neutron and pion beta decays, has taken on added interest recently in light of the superallowed results for V_{ud}. The Standard Model requires that

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

where V_{us} is determined from kaon decays and V_{ub} is taken from the decay rates for B mesons. This requirement on the quark-mixing matrix is referred to as unitarity. At present, the experimental values for the $|V_{ij}|$ yield a sum falling below unity by slightly more than two standard deviations. If we

Figure 2.18. A crack in the Standard Model? The superconducting storage ring at Brookhaven is currently being used to measure the muon anomalous magnetic moment, $g - 2$, to a precision of better than 1 ppm. Comparing experiment to theory provides a sensitive test of the Standard Model and proposed extensions. In fact, a recently published experimental result differed significantly from theory, prompting a reevaluation of the underlying theory and the discovery of an error. With 80% of the data yet to be analyzed, the physics community is watching this situation closely. *Photo courtesy of Ripp Bowman.*

are unable to explain this deviation in terms of conventional, strong-interaction corrections, then we must look for a solution in terms of new physics. For example, the presence of a right-handed charged gauge boson, $W_R^{\pm}$, which mixes slightly with the corresponding left-handed boson, $W_L^{\pm}$, of the Standard Model, could be the culprit. Similarly, effects involving virtual, supersymmetric particles—analogous to those entering the muon anomaly—or new tree-level supersymmetric interactions that transform leptons of one flavor into another, could produce an apparent violation of the unitarity requirement.

The potential implications of apparent quark-mixing nonunitarity underline the importance of testing the experimental and theoretical input entering the V_{ij} determinations. To that end, new experiments are under way at NIST to extract V_{ud} from measurements of the neutron lifetime and at LANSCE from measurements of the parity-violating asymmetry. A complementary measurement of V_{us} could also help resolve the quark-mixing unitarity question. A new experiment proposed at Brookhaven could produce a more precise value for V_{us}, whose current value was determined nearly 25 years ago. While the current uncertainty in $|V_{us}|^2$ is smaller than the apparent unitarity deviation, completion of a new measurement would solidify confidence in this parameter's contribution. (The magnitude of V_{ub} is too small to have an appreciable effect on the unitarity test.)

Other low-energy, charged-weak-interaction measurements will also contribute to our picture of the new Standard Model. In particular, a new measurement of the parameters that describe the decay of polarized muons—the Michel parameters—is planned at TRIUMF, with an expected improvement in experimental precision of 25- to 60-fold. Plans also exist for new measurements of parity-violating asymmetry parameters in nuclei such as rubidium or francium using atom traps.

Rare and forbidden processes. The symmetries of the Standard Model imply that various weak processes are either forbidden or highly suppressed—that is, rare. These symmetries include (i) lepton family number (L) conservation, in which, for example, electrons and their neutrinos cannot be transformed into muons or muon neutrinos; (ii) baryon number (B) conservation, in which the net number of quarks compared to antiquarks is not changed; and (iii) time-reversal invariance (T), according to which the dynamics of lepton and light-quark interactions do not depend on whether time runs forward or backward. In the Standard Model, B – L is conserved as well, though this symmetry is "accidental" and not the result of any deep theoretical consideration. The new Standard Model may not respect these symmetries, and any experimental discovery of their violation would provide important clues about the nature of the new theory.

Nuclear physicists are involved in a number of such symmetry tests (see "Looking for the Super Force," pages 74–75). In particular, the violation of T would imply the existence of a permanent electric dipole moment (EDM) of the neutron, electron, and/or neutral atoms. In classical, everyday physics, an EDM arises when two electric charges having opposite signs become permanently separated. Examples include ordinary molecules in which the average position of the valence electrons is separated from the center of the oppositely charged nucleus. For pointlike (or quasi-pointlike) objects such as an electron or neutron, however, quantum mechanics implies that the interaction of an EDM with a photon can only result when T is not respected. In the electroweak sector of the Standard Model, T is violated, though at a level currently beyond the ability of physicists to detect. The neutron EDM is correspondingly highly suppressed ($\leq 10^{-32}$ e cm), since it is generated by complicated effects involving virtual heavy quarks and gluons. Cosmological considerations, however, suggest the existence of a neutron EDM having a considerably larger magnitude, whose origins would lie in some version of the new Standard Model. The predominance of matter over antimatter in the universe implies that T must have been violated during the evolution of the universe. (Strictly speaking, these arguments require the presence of CP violation, which, according to CPT conservation, implies T violation.) While the Standard Model provides for T violation among heavy quarks in accordance with the observation of T-violating decays of kaons and B mesons, the magnitude of this T violation is not sufficient to have produced the observed matter-antimatter mismatch.

Scenarios for the new Standard Model that provide the requisite level of T violation also predict a neutron EDM in the vicinity of 10^{-28} e cm. Although current limits on EDM measurements fall short of this range ($\sim 10^{-25}$ e cm), new efforts are under way to improve these limits by two to four orders of magnitude, using cold and ultracold neutron methods. The implications of such improved sensitivity can be seen by noting that several scenarios for the new

Looking for the Super Force

Physicists have long believed that, when the universe was born, all the known forces of nature were unified into a single "super force." According to this picture, as the fireball of the Big Bang cooled during the evolution of the universe, the super force broke apart into different elements, namely, the gravitational, strong, weak, and electromagnetic forces familiar to us today. Although physicists have arrived at a partial description of the way in which these forces were unified at the inception of the universe, the current theory—the so-called Standard Model—is incomplete. It does not explain, for example, why the universe contains more matter than antimatter. Nor does it tell us how the strengths of the four known forces of nature become the same as we look back in time toward the earliest moments of the universe. And a quantum mechanical treatment of gravity is entirely missing from this theory.

The development of a more complete description remains one of the most compelling lines of research in physics today. One of the most powerful ideas used in this research is the idea of symmetry. Physicists believe that the universe was an exquisitely symmetric system at its birth. The breaking apart of the super force meant that, as the universe evolved, some of its original symmetry was lost, or "broken." One aspect of that symmetry involves the handedness of various particles. Just like humans, particles can be either left- or right-handed. When the universe was born, the super force did not distinguish between left- and right-handed particles—a symmetry known as "parity." We now know, however, that the weak interaction, which describes phenomena such as radioactive decay, involves only left-handed particles. In short, this interaction violates parity symmetry, and it does so to the maximum extent possible. How, then, did the symmetric universe evolve to render one (and only one) of the known forces entirely unsymmetric?

A variety of nuclear physics experiments now under way should provide important clues to the answers to such questions as this, at the same time testing various theoretical ideas about what lies "beyond" the Standard Model. Unlike experiments in high-energy physics, which involve collisions between very high-energy particles such as electrons and positrons, nuclear physics experiments involve processes at much lower energies. Moreover, these experiments must be extraordinarily precise, since most of the theoretical models for an "improved" Standard Model predict very small—but perceptible—deviations from the outcomes predicted by the current theory.

A number of these ongoing experiments exploit the parity-violating property of the weak interaction to filter out its effects from the other forces. At Los Alamos, for example, experiments are under way to study the parity-violating beta decays of neutrons. Similar experiments are either under way or planned at SLAC and Jefferson Lab to observe the parity-violating scattering reactions of electrons with other electrons and protons, respectively. The results of these measurements could teach us about the existence of previously unobserved heavy particles that might have been responsible for making the weak interaction parity-symmetric earlier in the universe's life. These measurements could also test for the presence of another symmetry—called "supersymmetry"—which predicts the existence of a very heavy partner particle for each of the currently known elementary particles. The existence of these "superpartners" may be responsible for the observed deviation of the muon anomalous magnetic moment from the value predicted by the Standard Model, and they could cause similar deviations in precise, low-energy parity-violation experiments.

Nuclear physicists at Los Alamos are undertaking another measurement that will shed light on the observed predominance of matter over anti-

E158 at Stanford. The photograph shows the liquid hydrogen target chamber and the giant dipole and quadrupole magnets of the E158 forward-angle spectrometer under construction at SLAC. E158 is designed to measure the tiny weak force between two electrons to search for clues to a new "superweak" force.

matter in the universe. This measurement involves a search for a permanent electric dipole moment (EDM) of the neutron, which would arise if the positively and negatively charged quarks in the neutron are, on average, spatially separated. The existence of an EDM is related to the matter-antimatter asymmetry, since both require the breakdown of "CP symmetry." We already know that CP symmetry is broken, as a result of studies of neutral K meson decays. Although the Standard Model contains enough CP violation to explain these decays, it does not provide a sufficient amount to account for the predominance of matter over antimatter in our universe. Theoretical models that do provide the requisite CP asymmetry also predict the existence of a neutron EDM large enough to be seen in the new experiments. Thus, the EDM search should test whether these ideas are right and help us understand why matter predominates in the observed universe.

Precision symmetry tests in nuclear physics have also found a new application in the study of low-energy strong interactions. While the theory of the strong force is well tested in high-energy scattering experiments, the ways in which it binds quarks and gluons into nucleons and nuclei remain only partially understood. Measurements of parity-violating weak interactions between electrons and nucleons and between two nucleons are poised to shed new light on the low-energy strong interaction. The recent program of parity-violation experiments at MIT and Jefferson Lab have shown that—over certain distance scales in the nucleon—the "sea" of strange quarks in the nucleon's interior contributes very little to its electromagnetic properties, contrary to a variety of theoretical predictions. Additional parity-violation experiments now under way will extend these initial studies to cover other distance scales. Moreover, the MIT experiment has uncovered a new mystery involving the effects of the nucleon "anapole moment" on the weak electron-nucleon interaction, suggesting that its effects may be considerably larger than predicted by theory. The anapole moment of the cesium nucleus has also recently been measured in atomic physics experiments, and its effects are similarly in disagreement with theoretical expectations. The anapole moment arises from a complicated interplay of strong and weak interaction effects, and understanding it could have potentially important implications for the interpretation of other precision weak-interaction measurements. A new measurement of radiative neutron capture on the proton, being carried out at Los Alamos, may provide new insights into the anapole moment puzzle.

Standard Model have already been ruled out by the *current* neutron EDM limits. These current limits have also posed important challenges for quantum chromodynamics (QCD)—the strong sector of the Standard Model—where T violation arises through a term parameterized by a quantity θ_{QCD}. The present neutron EDM limits imply $|\theta_{QCD}| < 6 \times 10^{-10}$, which is unnaturally small compared with the other QCD parameters. (A recent limit on the EDM of ^{199}Hg has tightened the constraint on θ_{QCD} by a factor of four.) This situation has motivated considerable work in particle theory, leading, for example, to the proposal of a new light particle, the axion, that might contribute to the dark matter.

Time-reversal symmetry may also be broken in a way that respects parity invariance, and a number of searches for such effects are under way. The emiT collaboration has produced new limits on the T-violating, parity-conserving correlation between the spin of the neutron and the momenta of its daughters in neutron beta decay. A measurement of a similar correlation coefficient for ^{37}K using neutral atom traps is being undertaken at TRIUMF. Future measurements of parity-conserving, T-violating effects using hadron-hadron scattering may also be pursued at TRIUMF and COSY, while new studies of T-violating, parity-conserving correlations in polarized, epithermal neutron transmission in heavy nuclei is a possibility for the SNS. Recent theoretical work has demonstrated that such studies complement EDM searches, which are sensitive to parity-conserving T violation only under specific assumptions.

Tests of B and L conservation have reached similarly impressive levels of precision. While the implications for nucleon decay of possible B nonconservation, as predicted in many new physics scenarios, have fallen within the purview of particle physics, nuclear physicists could, in principle, look for B nonconservation via n-$\bar{n}$ oscillations with high-intensity neutron sources. Such oscillations transform quarks into antiquarks, thereby changing the net number of quarks versus antiquarks. In the leptonic sector, the most stringent tests of L conservation have been performed by searching for muon to electron conversion in nuclei and for the radiative process $\mu \to e\gamma$. Such transitions can occur, for example, in supersymmetric grand unified theories (SUSY GUTs), whose predicted branching ratios lie below current experimental limits. Future experiments at PSI ($\mu \to e\gamma$) and Brookhaven (μ-e conversion) will improve on the current experimental limits by several orders of magnitude, making them sensitive to SUSY GUT predictions. Conversion in nuclei offers particular advantages, since the coherent exchange of virtual photons can be sensitive to properties of L-violating new physics not accessible with real photons. Searches for another type of L-violating process—neutrinoless double beta decay—have important implications for the identity and mass of the neutrino (see pages 81–82).

Weak probes of hadron structure. Historically, studies of weak interactions of hadrons have been motivated by a desire to test the Standard Model prediction for the weak interaction involving quarks only. The present success of the Standard Model, however, has changed the motivation for these studies. Weak quark-quark interactions are complicated by their interplay with strong interactions, and theorists' ability to compute the latter in the context of QCD has yet to reach the level with which purely electroweak processes can be predicted. Consequently, attention has shifted to viewing the hadronic weak interaction as a *tool* for probing low-energy QCD. This new emphasis has two primary facets: (i) semileptonic weak probes of the structure of hadronic systems and (ii) the study of parity-violating, purely hadronic phenomena.

During the past decade, a well-defined program of measurements has been developed whose goal is to study the spatial distribution and magnetic properties of strange quarks in the nucleon, using parity-violating scattering of polarized electrons from hadronic targets. The resulting asymmetries arise from the interference of the parity-conserving electromagnetic amplitude and the parity-violating neutral weak amplitudes. Since the former have been well studied over the years with electron-scattering experiments, these asymmetry measurements provide information on the neutral weak e^-N interaction. A comparison of the latter with the electromagnetic e^-N interaction allows one to determine the contributions of strange quarks in the nucleon to the electromagnetic properties of the nucleon.

These experiments are of keen interest to hadron structure physicists. In the simplest model approximation for the structure of the nucleon, only up and down quarks contribute to its low-energy properties. High-energy, deep inelastic scattering experiments, however, imply that the structure of the nucleon is considerably more complicated, involving both valence up and down quarks as well as a "sea" of gluons and quark-antiquark pairs. Since strange quarks occur in the nucleon only as part of the sea, the parity-violation experiments provide for the first time a means of isolating sea quark contributions to the low-energy electromagnetic properties of the nucleon. The results of this program will reveal whether sea quarks are essentially inert at low energies, or whether their effects are hidden in the phenomenological parameters of simple nucleon models. Given the importance of this question, considerable theoretical work using lattice QCD, dispersion theory, chiral perturbation theory, and other methods has been motivated by these measurements at MIT-Bates, Jefferson Lab, and Mainz.

The measurements at MIT-Bates have also determined the neutral weak "axial vector" e^-N interaction. A comparison of the result with the charged weak amplitude entering neutron beta decay—after taking into account higher-order electroweak effects—has revealed a discrepancy with theory having potential implications for the interpretation of other high-precision semileptonic measurements. A measurement of parity-violating electron-nucleus scattering is also planned, using a lead target, to determine the neutron distribution in heavy nuclei. The results of this measurement may also provide important insights into the nature of neutron stars as well. While not intended as a nucleon structure study, the latter measurement illustrates the use of the weak interaction to probe new aspects of many-body nuclear dynamics.

A number of new studies of parity-violating, purely hadronic processes are also under way. Of particular interest is the long-distance component of the parity-violating NN interaction. Since the $W^{\pm}$ and Z^0 bosons, which mediate weak interactions among quarks, are almost 100 times heavier than the nucleon, direct exchange of these particles between nucleons in a nucleus is highly suppressed. Consequently, the long-range, parity-violating NN force is mediated by the exchange of pions, where one of the parity-violating πN interactions results from weak interactions among light quarks. Recent theoretical work has shown that this interaction could be sensitive to the effects of light, nonstrange sea quarks and to the consequences of the breakdown of chiral symmetry in QCD. Experimentally, discrepancies exist among various determinations of the long-range parity-violating NN force. Measurements of the photon polarization in the decay of ^{18}F are consistent with no effect, whereas the recent determination of the cesium anapole moment (a parity-violating moment that can be probed by virtual photons), taken in conjunction with results from parity-violating pp scattering, implies a sizable, nonzero effect. Future measurements in few-body systems could help resolve this puzzle, providing important input to hadron structure theorists. A measurement of the asymmetry in $\vec{n} + p \rightarrow d + \gamma$ is under way at Los Alamos, while a future measurement of neutron spin rotation in helium is planned for NIST and possibly the SNS.

Neutrons and the new Standard Model. One "nucleus," the neutron, provides a particularly simple laboratory for studying beta decay—the lifetime and the angular correlations and polarizations of the produced proton, electron, and antineutrino—and for probing new particle properties such as EDMs.

The pure vector–axial vector nature of the Standard Model leads to a maximal violation of parity, or mirror symmetry. Why nature should violate mirror symmetry is not understood, but one popular notion is that the violation is a low-energy phenomenon: The larger grand theory that describes physics at high energies beyond the Standard Model would be left-right symmetric. The new interactions responsible for the symmetry restoration at high energies would have some consequences in our low-energy world, however, including subtle departures from the exact vector–axial vector Standard Model predictions for neutron beta-decay angular correlations.

Neutron beta decay has the potential to clarify the unitarity discrepancy in the quark-mixing matrix discussed earlier. The measurements of $|V_{ud}|$ have been done both with complex nuclei and with neutrons. Studies on complex nuclei are complicated by the need to correct the experimental results for the effects of isospin mixing in the nuclear wave functions and for a variety of radiative phenomena associated with the Coulomb field of the nucleus. It is not currently clear that more accurate beta-decay studies in complex nuclei will improve the accuracy of the unitarity test, because of the inherent theoretical uncertainties in the radiative correction calculations. Thus, progress may depend on improved neutron beta-decay studies.

The extraction of $|V_{ud}|$ requires experimenters to combine measurements of the neutron lifetime and the angular correlations between the spin vector of the neutron and the momentum vector of the emitted electron. Although accurate and consistent measurements of the neutron lifetime have been done, the neutron-beta asymmetry results obtained with cold neutron beams at reactors have yielded inconsistent results. These experiments typically face several serious challenges. One is a determination of the neutron polarization, which is done by reflecting the neutron beam from a magnetized multilayer supermirror. The polarization varies with neutron wavelength and with the position and angle in the neutron beam, complicating the polarization measurement. A second complication is the small fraction of neutrons that decay while passing through the spectrometer (typically one in 10^6). The remaining neutrons are a source of background. Finally, the detectors that observe the emitted electron must have an extremely well-characterized response. In order to minimize these systematic effects, new techniques have been developed that employ pulsed cold neutron beams at accelerators and ultracold neutrons (UCNs), which are neutrons that have such low velocities that they can be held in bottles for long periods, making a compact source of neutrons. With intense sources of pulsed cold neutrons and UCNs coming on-line soon, and with even higher-intensity sources being designed, there is the prospect for significant experimental progress (see Figure 2.19).

Similar opportunities exist for improving limits on the neutron EDM. As discussed previously, elementary particles, as well as composite systems such as the neutron and nuclei, can have EDMs—a separation of charge along their spin directions—only if both parity and CP/T are violated. The increased precision of recent neutron EDM searches has come from using intense sources of UCNs, which reduce systematic effects associated with motional magnetic fields. An experiment currently running at ILL should yield, by 2004, a tenfold improvement in sensitivity. The recent development of superthermal sources of UCNs will, because of their higher intensities, allow further significant progress.

New Neutrino Physics

Nuclear physics has a long and distinguished role in neutrino physics (see "A History of Neutrinos," page 78). The neutrino was postulated 70 years ago in order to maintain energy conservation in nuclear beta decay. The prediction that nuclear fusion in the solar core would produce an enormous flux of neutrinos led Ray Davis, a nuclear chemist, to launch the field of neutrino astrophysics. The startling discovery he made—a solar neutrino flux only one-third of that

A History of Neutrinos

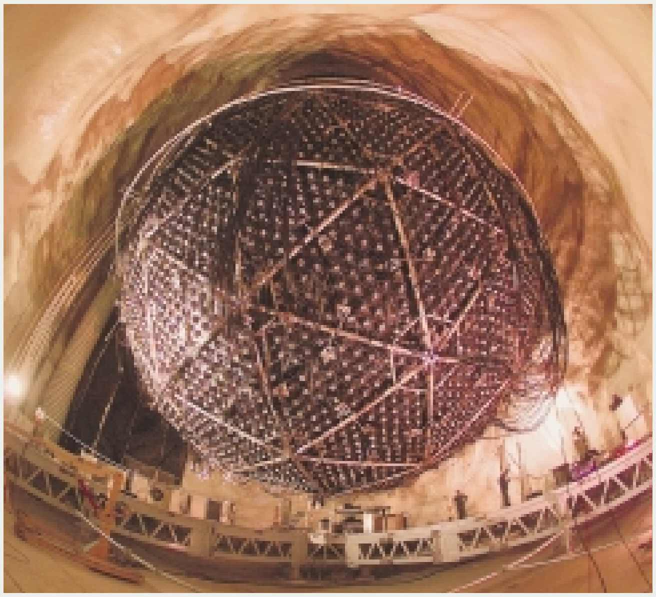
In the 1930s a crisis arose in nuclear physics. It appeared that energy was not conserved in beta decay. Wolfgang Pauli therefore proposed the existence of the neutrino to save this fundamental principle, but the particle would not be observed experimentally for another 25 years. Neutrinos are uncharged, interact only weakly, and are very difficult to detect. Now we know there are actually three kinds of neutrinos, the electron neutrino of beta decay, the muon neutrino, and the tau neutrino.

In 1968 a bold experiment was built by Ray Davis and his collaborators deep in the Homestake gold mine. They wanted to see if the sun was indeed powered by thermonuclear fusion, as proposed by Hans Bethe; neutrinos emitted by the sun would be a clear signature of this process. The experiment, using ^{37}Cl nuclei in 615 tons of cleaning fluid, successfully observed the postulated neutrinos, but the number seen was only about a third of the number expected.

It was widely supposed that either the experiment or the solar model was flawed, but Bruno Pontecorvo suggested that electron neutrinos might "oscillate" into some mixture of electron and muon neutrinos. Since the experiment was not sensitive to muon neutrinos, the flux would appear to be too low.

With the development of the Kamiokande, Soviet-American Gallium, GALLEX, and SuperKamiokande experiments, it became clear in the 1990s that only new neutrino properties could explain the observations. Neutrino oscillations fit the data well. In addition, data from SuperKamiokande and other experiments on neutrinos produced in the Earth's atmosphere gave compelling evidence that muon neutrinos were converting into tau neutrinos. Travelling the distance of the Earth's diameter, however, the electron neutrino was unchanged.

The Sudbury Neutrino Observatory was built to provide direct evidence for or against the presence of other flavors in the solar flux. The target consists of 1000 tons of heavy water (deuterium oxide), where neutrinos can induce three different kinds of reaction. The charged-current reaction is sensitive only to the electron neutrinos from ^{8}B decay in the sun, the neutral-current reaction is equally sensitive to all three flavors, and the elastic scattering reaction is sensitive mainly to electron neutrinos but also, with a cross section only one-sixth as big, to muon and tau neutrinos, as well. First results from SNO, when combined with the SuperKamiokande results, provide strong evidence that electron neutrinos oscillate. This observation has confirmed our understanding of how the sun generates energy. The evidence for neutrino oscillations also provides the first strong evidence for new physics beyond the Standard Model. Future experiments will provide much more detailed information about the effect of neutrinos on the evolution of the universe, whether there are sterile neutrinos (that is, neutrinos that do not have the normal weak interaction couplings), and whether CP and CPT are valid symmetries in the neutrino sector.



Counting nature's phantoms. The SNO neutrino detector, shown here before it was filled with water, is located 2000 m underground at the Creighton mine in Canada. The geodesic structure that supports the detector's 9500 photomultiplier tubes is shown inside the rock cavity excavated for the detector. The complete detector contains 7000 tons of ultrapure water, surrounding a 12-m-diameter transparent acrylic sphere filled with 1000 tons of ultrapure heavy water.

predicted by models of the sun—very recently led to the first evidence for physics beyond the Standard Model. We now know that neutrinos have mass and can change their identities as they propagate. The implications of such phenomena touch issues ranging from the nature of the dark matter that pervades the universe to the description of the elementary forces at energies far beyond the reach of accelerators.

Solar and atmospheric neutrinos. Davis's work was originally motivated by the desire to better understand the nuclear reaction chains that govern the synthesis of four protons into a helium nucleus deep in the solar core. The result of competition among various reaction chains depends sensitively on the solar core temperature and other astrophysical parameters. The neutrinos produced as a by-product of these nuclear reactions carry, in their fluxes and spectral distribution, a detailed record of the reaction chains. Thus, a careful program of experiments—both solar neutrino flux measurements and laboratory experiments to determine the strength of the nuclear reactions by which the sun produces neutrinos—could test whether our understanding of the solar interior is complete.

However, because neutrinos react so weakly, they can be detected only through heroic experiments involving, typically, kiloton detectors and event rates measured in a few counts per day. These experiments must be conducted deep underground to escape backgrounds arising from cosmic rays. Davis's radiochemical chlorine detector recorded primarily the highest-energy solar neutrinos, those produced in the beta decay of ^{8}B in the solar core. His result has now been confirmed in experiments carried out with water Cerenkov detectors within a mine in Japan. The second of these, SuperKamiokande, measures solar neutrinos event by event. The results confirm that the ^{8}B neutrino flux is less than half that predicted by the standard solar model. In addition, two radiochemical experiments employing gallium targets have confirmed that the low-energy solar neutrino flux is also less than the standard solar model prediction.

The pattern of solar neutrino fluxes that emerged from these experiments was very difficult to reconcile with plausible changes to the solar model. Many in the scientific community therefore began to suspect that, instead, new particle physics was the correct explanation. The leading hypothesis became neutrino oscillations, a phenomenon forbidden in the Standard Model, which requires neutrinos to be massless. If, however, neutrinos have small masses, then the electron-type neutrinos produced by solar fusion reactions can be transformed into neutrinos of a different type (or flavor) as they travel from the solar core to the Earth. As the solar neutrino detectors mentioned above have either a diminished or no sensitivity to other neutrino flavors, these transformed neutrinos would then appear to be "missing."

This proposed solution would have far-reaching consequences. The Standard Model has withstood two decades of high-precision accelerator and nonaccelerator tests; the discovery of neutrino mass would be the first hint of physics beyond that model. In many theories, neutrino masses are connected with physics at very high energies, far beyond the reach of the most powerful particle accelerators. Neutrino masses could have profound implications for cosmology, perhaps providing part of the invisible dark matter that appears to influence the expansion of our universe and the formation of galaxies and other "large-scale structure" within

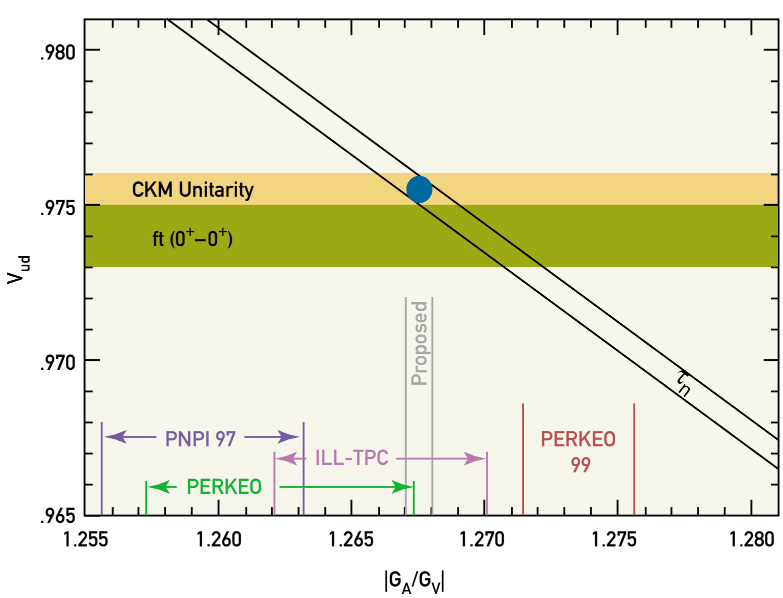


Figure 2.19. A role for cold neutrons. Measurements of the asymmetry of neutron beta decay (see text) determine the ratio of the axial to vector coupling constants, G_A/G_V. Measurements of the neutron lifetime τ_n and muon decay connect this ratio with V_{ud}, an element of the quark-mixing matrix. The ranges allowed for G_A/G_V, measured by four recent experiments at reactors, are shown, together with the precision expected in proposed experiments using pulsed cold neutrons and ultracold neutrons (UCNs). The blue ellipse shows the precision anticipated when the new measurements are combined with the existing value of τ_n. An improved measurement of τ_n using UCNs, now under way, should substantially reduce the uncertainty in that parameter, leading to a further reduction in the uncertainty in V_{ud} and a resolution of the inconsistency between values of V_{ud} obtained from superallowed nuclear beta decay and from requiring unitarity of the CKM matrix.

Figure 2.20. Experiments underground. This equipment for the Borexino solar neutrino experiment is shown in Hall C of the underground Gran Sasso Laboratory in Italy.

it. Neutrino oscillations could also affect supernovae, the violent explosions marking the deaths of massive stars, as well as the synthesis of new elements by such explosions.

These exciting implications make the resolution of the solar neutrino problem all the more urgent. The Super-Kamiokande detector was the first of a new generation of experiments allowing high count rates and event-by-event detection of solar neutrino interactions. The detector consists of 50 kilotons of ultrapure water, surrounded by 13,000 phototubes, which record the light produced when solar neutrinos scatter off electrons in the water. To avoid cosmic-ray backgrounds, the experimenters built the detector deep underground in the Kamioka mine. The second such detector, the Sudbury Neutrino Observatory (SNO), is now operating in a nickel mine in Ontario, Canada, 2100 m below the surface. Built by a Canada-U.S.-U.K. collaboration, SNO's central vessel contains 1000 tons of heavy water. A third detector, Borexino, is now being prepared in the Gran Sasso Laboratory in Italy (Figure 2.20). This experiment is designed to measure lower-energy neutrinos produced in the solar core.

The SuperKamiokande and SNO detectors both measure the high-energy ^{8}B neutrinos, but with a subtle difference. The nuclear reaction used in SNO, $\nu_e + d \rightarrow p + p + e^-$, is triggered only by electron neutrinos. The electron scattering reaction in SuperKamiokande, $\nu_e + e^- \rightarrow \nu_e + e^-$, though primarily sensitive to electron neutrinos, is also triggered by muon and tau neutrinos (the other neutrino flavors). The SNO experiment very recently reported the results from its first year of data-taking. The rate of neutrino events is less than that seen in SuperKamiokande, with the difference being significant at a confidence level exceeding 99.9%. This is the first demonstration that a substantial portion of the solar neutrino flux—on reaching Earth—is no longer of the electron type. By exploiting another reaction, $\nu + d \rightarrow n + p + \nu$, SNO can operate in a second mode to measure the neutrino flux independent of flavor. Thus, the missing neutrinos should soon be seen directly in the SNO detector.

SuperKamiokande has also exploited a second neutrino source, the Earth's atmosphere, where neutrinos are produced by cosmic-ray interactions. These higher-energy neutrinos travel different distances to the detector, depending on whether they are produced above the detector or on the opposite side of the Earth. This permits the experimenters to conduct a powerful test of oscillations, as oscillation probabilities vary with distance. A distinctive signal emerged from the SuperKamiokande atmospheric neutrino measurements, with the neutrinos from below sharply reduced in flux compared to the neutrinos from above. A careful analysis shows that the atmospheric oscillations involve muon neutrinos transforming into tau neutrinos.

Some remarkable conclusions can be drawn from this new neutrino physics. Neutrino oscillations depend on the difference in the squares of neutrino masses, $\delta m^2 = m_2^2 - m_1^2$. The value $\delta m^2 \cong 0.003$ eV^2, deduced from the atmospheric oscillation results, places a lower bound on neutrino masses: At least one neutrino must have a mass $\gtrsim \sqrt{0.003}$eV ~ 0.05 eV. It follows that neutrinos must be a significant component of particle dark matter. The cosmological background neutrinos produced in the Big Bang are at least as important as the visible stars in contributing to the mass of the universe. A second consequence of this mass is connected with a popular explanation for why neutrinos are so much lighter than their charged partners. The "seesaw mechanism" relates the tau neutrino mass to the tau mass m_D and to the new high-energy scale M_R: $m_\nu \sim m_D^2/M_R$. The atmospheric neutrino results thus yield $M_R \sim 0.3 \times 10^{15}$ GeV, a value similar to the grand unification scale of ~10^{16} GeV. Thus, it is possible that the new neutrino results are directly probing the physics governing the next level of unification beyond the Standard Model.

One puzzle also emerges from the atmospheric and solar neutrino results. There was a theoretical prejudice—arising in part from weak interaction patterns among the quarks—that neutrino oscillation "mixing angles" would be small, that is, that the states of definite mass would not be too different from the flavor eigenstates. In fact, the atmospheric neutrino results require mixing angles that are maximal. There are also indications that the solar neutrino results favor large mixing angles. Perhaps this surprise is an important clue to the pattern of physics beyond the Standard Model.

Neutrino masses and double beta decay. As neutrino oscillations probe only δm^2, rather than the absolute scale of neutrino masses, we need other types of neutrino mass measurements. One important class of such experiments involves searches for the kinematic effects of nonzero neutrino masses. A massive electron neutrino will alter the spectrum of electrons emitted in beta decay, whereas a massive muon neutrino will alter the energy of the muon produced in pion decay, $\pi^+ \to \mu^+ + \nu_\mu$. Thus, neutrino mass limits—or neutrino masses—can be extracted in careful studies of such reactions. Such spectral measurements have a long history in nuclear physics: Wolfgang Pauli first postulated the neutrino in 1930 to preserve energy conservation in beta decay.

Owing to its small energy release (18.6 keV) and attractive half-life (12.3 years), tritium beta decay has become a favorite testing ground for the electron neutrino mass. Experimenters carefully study the electron spectrum in $^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$, particularly near the electron endpoint energy. A small neutrino mass will shift that endpoint slightly, while producing a characteristic distortion of the spectrum. The challenge is to distinguish that distortion, given finite detector resolution, electron energy loss in the tritium source, energy losses due to population of atomic excited states in the decay, and other such systematic effects.

Such experiments constrain the quantity

$$m_\nu^2 = \sum_i |U_{ei}|^2 m_i^2$$

where $|U_{ei}|^2$ is the probability for the ith neutrino mass eigenstate to couple to the electron, and m_i is the corresponding mass. Over the past two decades, the precision of experiments has improved almost a thousandfold, though many have been plagued by troubling systematics that produced a negative m_ν^2 as the best value. This systematic is absent in the most recent and precise data of the Mainz group, from which an electron antineutrino mass limit of 2.2 eV (95% confidence level) has been deduced.

The Mainz experiments and most of the other recent tritium experiments have involved large magnetic spectrometers. The next-generation experiment of this type has as its goal a mass limit of 0.5 eV. New types of detectors are also under development, such as calorimeters based on rhenium as a source, that promise 1-eV resolution and could measure total energies (including atomic excitations).

Another important class of neutrino mass measurements is connected with the question of the behavior of the neutrino under particle-antiparticle conjugation. Most particle-antiparticle pairs are distinct particles: The charges of the electron and positron, for example, allow them to be readily distinguished from one another. But what if there were a particle with no electric charge and no charges of any other kind? What would distinguish particle from antiparticle? Among the Standard Model fermions, there is only one example of such a particle—the chargeless neutrino. The question of what distinguishes the neutrino from the antineutrino turns out to be very profound, connected with the nature of the neutrino's mass. The possibility that the neutrino might be identical to the antineutrino allows the neutrino to have a special kind of mass—called a Majorana mass—that violates one of the important conservation laws of the Standard Model.

This question of the particle-antiparticle nature of the neutrino is associated, in turn, with a very rare phenomenon in nuclear physics. Certain nuclei exist that appear to be stable, but in fact decay on a time scale roughly 10^{12} times longer than the age of our universe. This process, double beta decay, involves a spontaneous change in the nuclear charge by two units, accompanied by the emission of two electrons and two antineutrinos. Following 30 years of effort, double beta decay was finally detected in the laboratory about a decade ago. It is the rarest process in nature ever measured. Physicists are currently engaged in searches for a still rarer form of this process, one in which the two electrons are emitted without the accompanying antineutrinos. The existence of such "neutrinoless" double beta decay directly tests whether the neutrino is a Majorana particle.

The observation of neutrinoless double beta decay would have far-reaching consequences for physics. It probes not only very light neutrino masses—current limits rule out Majorana masses above ~1 eV—but also very heavy ones, up to 10^{12} eV. It measures interference effects between the various neutrino families not easily tested elsewhere. The existence of Majorana neutrinos is the basis for the seesaw mechanism discussed above, which explains why neutrinos are so light and relates small neutrino masses to physics occurring at energy scales 10^{12} times greater than those accessible in the most powerful accelerators. The conservation law tested in neutrinoless double beta decay is connected, in many theoretical models, with the cosmological mechanism that produced a universe rich in nucleons (rather than antinucleons).

Recent experimental progress in this field has been rapid. Thirty years of effort was required before two-neutrino double beta decay, a process allowed by the Standard Model, was observed in 1987. Today, accurate lifetimes and decay spectra are known for about a dozen nuclei. This "standard" double-beta-decay process is crucial to theory, providing important benchmarks for the nuclear physics matrix element calculations that are done to relate neutrinoless beta-decay rates to the underlying neutrino mass.

Progress in searches for neutrinoless double beta decay has been equally impressive. Extraordinary efforts to reduce backgrounds by means of ultrapure isotopically enriched materials, improved energy resolution, and shielding of cosmic rays and natural radioactivity have produced a "Moore's law" for neutrinoless double beta decay: a twofold improvement in lifetime limits every two years over the past two decades. The lower bound for the lifetime for this process in the nucleus ^{76}Ge, ~ 2×10^{25} years, corresponds to a Majorana mass limit of 0.4–1.0 eV, with the spread reflecting uncertainties in the nuclear matrix elements.

A new generation of experiments is now being proposed to probe Majorana masses in the range of 0.03–0.10 eV, a goal set in part by the value δm^2 ~ 0.003 eV^2 deduced from the SuperKamiokande atmospheric neutrino results. These ultrasensitive experiments are confronting several new challenges. A new background—the tail of the two-neutrino process—can be avoided only in detectors with excellent energy resolution. Detector masses must be increased by two orders of magnitude: The counting rate is a fundamental limit at the current scale of detector masses (~10 kg). As the detector mass is increased, corresponding progress must be made in further reducing backgrounds through some combination of active shielding, increased depth of the experiment, and purer materials.

The current generation of experiments includes the Heidelberg-Moscow and IGEX ^{76}Ge detectors, the Caltech-Neuchatel effort on ^{136}Xe, and the ELEGANTS and NEMO-3 ^{100}Mo experiments. All have comparable goals (lifetime limits in excess of 10^{25} years) and comparable masses (~10 kg). The Heidelberg-Moscow experiment has acquired more than 35 kg-years of data and has established the stringent lifetime limit mentioned above (2×10^{25} years). All of these experiments are being conducted outside the U.S., though several have U.S. collaborators.

The new experiments under consideration include enriched ^{76}Ge detectors, a cryogenic detector using ^{130}Te, ^{100}Mo foils sandwiched between plates of plastic scintillator, a laser-tagged time-projection chamber using ^{136}Xe, and ^{116}Cd and ^{100}Mo in Borexino's Counting Test Facility. Some of these proposals are quite well developed, while others are still in the research and development stage. The detector masses are typically ~1000 kg. Several proposed experiments depend on the availability of enrichment facilities to produce the requisite quantities of the needed isotopes.

These experiments represent a crucial opportunity to advance the field of neutrino physics. If the δm^2 now deduced from the atmospheric neutrino experiments is taken as the scale of neutrino masses and if mixing angles are large, then the prospects for finding neutrinoless double beta decay in the next generation of experiments is excellent—if the neutrino has a Majorana mass. Crucial in formulating a new Standard Model incorporating massive neutrinos will be information on the size of the Majorana masses and on the charge conjugation properties of neutrinos.

Terrestrial neutrinos. Neutrino oscillations can also be studied in controlled laboratory experiments, with the neutrino source being a reactor or accelerator. There is an exciting—and controversial—signal for oscillations in one such experiment. The LSND collaboration has found an excess of events attributable to electron antineutrinos, signaling the oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$. The result was unexpected, because it corresponds to a δm^2 different from that found in the solar and atmospheric neutrino experiments. As three neutrinos permit only two independent mass differences, the LSND results then require a fourth neutrino, one that is "sterile," lacking the usual weak interactions. The MiniBooNE experiment at Fermilab is designed to verify or refute the LSND findings.

While laboratory neutrino oscillation experiments have a rich history, the atmospheric and solar neutrino results have greatly stimulated the field by establishing target values for the δm^2 values that must be reached in such experiments. The smaller the value of δm^2, the longer the distance the neutrino must propagate before the effects of oscillations can be detected—and thus the smaller the rate of neutrino reactions in the target (since the flux drops off with distance from the source). The atmospheric neutrino results have therefore stimulated several "long baseline" experiments. One will use Fermilab's neutrino beam in conjunction with a detector mounted in Soudan, an underground laboratory in Minnesota. Another such experiment is already under way in Japan. The initial results, while not definitive statistically, show a reduced counting rate consistent with the oscillation probability found in the SuperKamiokande atmospheric neutrino measurements.

The δm^2 favored by the solar neutrino experiments is still smaller, and thus more difficult for terrestrial experiments to probe. The first experiment to attempt to reach the necessary sensitivity is under construction in Japan. The Japanese-U.S.-Hungarian collaboration is "recycling" the Kamioka solar neutrino detector, replacing the water with liquid scintillator. The neutrino sources are various commercial power reactors in Japan, which produce electron antineutrinos as a by-product of nuclear fission. As these reactors power up and down, the KamLAND experiment will sample antineutrinos from different locations and thus from different distances.

In conclusion. The field of neutrino astrophysics began 35 years ago with the efforts of nuclear physicists to understand the mechanisms responsible for solar energy generation. In the past two years, this field—now a partnership among nuclear physics, particle physics, and astrophysics—has led to a dramatic discovery: Neutrinos have mass and "mix" with one another. This finding demonstrates that our current Standard Model of fundamental particle interactions is incomplete. It also provides our first clue to the nature of physics beyond the Standard Model. The implications are profound. Many theorists believe neutrino masses are related to phenomena occurring at energies 10^{12} times those currently available at the largest accelerators. The first component of the mysterious dark matter that pervades our universe has been identified: Neutrinos are at least as important as the visible stars in contributing to the universe's mass and energy budget. Neutrino mixing also has important implications for astrophysical phenomena ranging from Big Bang nucleosynthesis to supernova explosions.

For example, neutrino oscillations could hold the key to the spectacular stellar explosions known as core-collapse supernovae. At the end of stellar evolution, a massive star forms an inert iron core that eventually collapses under its own weight, forming a neutron star or black hole. During this process, the outer mantle of the star is ejected, enriching the interstellar medium in new nuclei. While the supernova mechanism is poorly understood—most numerical simulations fail to produce successful explosions—it is believed that the neutrinos radiated by the newly formed neutron star help the mantle ejection. Almost all of the energy liberated in the core collapse is carried off by these neutrinos. If neutrinos undergo oscillations, the energy deposited by neutrino reactions in the star's mantle can increase, aiding the explosion. Neutrino oscillations can also affect the neutron/proton chemistry of the nucleon gases blown off the star. Important processes in nucleosynthesis are governed by this chemistry. Thus, it is quite possible that neutrino oscillations alter supernova nucleosynthesis in an important way. In particular, the rapid neutron-capture process, or r-process, by which about half of the heavy elements found in our galaxy were produced, is particularly sensitive to such effects. Thus, it could be that a fossil record of supernova neutrino oscillations lies hidden in the abundance pattern of the heavy elements.

Outlook

The present generation of solar neutrino experiments, including SNO and Borexino, will be in full operation during the next five years. There are also efforts under way to probe neutrino oscillations under the controlled conditions allowed by accelerator and reactor neutrino sources: Nuclear physicists are playing major roles in experiments such as KamLAND and MiniBooNE. Both classes of experiment have the opportunity to shed considerable light on the issue of neutrino masses and mixing angles.

The discoveries with solar and atmospheric neutrinos are now stimulating new experiments. The long-standing puzzle of the behavior of the neutrino under charge conjugation—Is the neutrino its own antiparticle?—may be resolved by new efforts to detect double beta decay, using detectors that are a hundred times more massive than those currently employed in this field. It is also already clear that a new generation of solar neutrino experiments will be needed beyond SNO and Borexino to study low-energy neutrinos. Finally, there is great interest in supernova neutrino observatories that can monitor our galaxy continuously for core-collapse supernovae.

Neutrino experiments—as well as experiments on double beta decay, dark matter, and nucleon decay—must be conducted deep underground to escape backgrounds associated with cosmic-ray muons. The next-generation experiments will be so sensitive that they need overburdens of more than a mile of rock. The importance of these experiments became apparent during the long-range planning process and has led the nuclear science community to propose construction of the world's deepest and most sophisticated underground laboratory as a principal component of our long-range plan. The *National Underground Science Laboratory* would provide opportunities not only in nuclear science, but also in high-energy physics, earth science, geomicrobiology, and a variety of applied fields. The closure of the Homestake mine in Lead, South Dakota, presents an exceptional opportunity to realize this initiative.

Standard Model tests in nuclear physics extend far beyond neutrinos. The nucleus is a versatile laboratory for isolating new interactions and for testing important symmetries. Experiments on superallowed beta decay and on the anomalous magnetic moment of the muon are placing important constraints on possible departures from the Standard Model. The baryon number asymmetry of our universe is motivating ever more sensitive searches for violations of time-reversal symmetry, manifested as nonzero nuclear and neutron electric dipole moments. Furthermore, our understanding of Standard Model weak interactions between nucleons is still incomplete, motivating studies of parity violation in nucleon scattering and within nuclei.

As the simplest unstable nucleus, the neutron is a special candidate for such studies. The community's *Neutron Initiative* will develop intense pulsed sources of cold neutrons and ultracold neutrons (UCNs). We have a unique opportunity for advancing fundamental neutron physics by developing a high-intensity, pulsed cold neutron beamline at the SNS. Recent technical advances have also opened the door to new sources of UCNs. A UCN facility in the U.S. would stimulate many important advances in precision symmetry tests. As in the case of neutrino physics, new phenomena are very likely within the grasp of the next generation of neutron experiments.

3. Facilities for Nuclear Science

Since its earliest days, nuclear science has been driven by experiment. The availability of state-of-the-art accelerator facilities, detector systems, and data acquisition and processing tools has been critical to progress in the field. Accordingly, nuclear physics has evolved dramatically over the past decade, as two very large, complex, and powerful facilities have been brought on-line. At the same time, the range of phenomena addressed by the field has moved to smaller distance scales and higher energies. Nuclear physics is, however, not defined by a single frontier. Low-energy facilities continue to be an important part of the enterprise. In fact, construction of a large, new low-energy facility, the Rare Isotope Accelerator (RIA), is the highest priority for new construction in the present document (see pages 124–127). RIA will explore the frontier at the limits of nuclear existence, rather than at small distance scales or high energy densities.

A variety of accelerators with a range of characteristics is needed to cover the range of beam species and energies needed for nuclear physics. In a similar way, detector systems developed for nuclear physics have an enormous range of capabilities and characteristics. While most of these detectors are tailored to match the requirements and properties of accelerator facilities, not all of nuclear physics is carried out at accelerators. Complex detectors, such as large underground solar and supernova neutrino detectors, are also designed and built for stand-alone experiments.

The design, development, and improvement of these facilities—the technical underpinnings of our field—often demand technological capabilities that push the state of the art. This environment of innovation provides an excellent training ground for students.

Tools of the Trade: Major Accelerator Facilities

High-energy nuclear physics facilities. Since the 1996 long-range plan was prepared, world-leading accelerator facilities have been commissioned at Brookhaven and at Jefferson Lab. These facilities have dramatically altered the landscape of nuclear physics in the U.S. The original motivations that led to the construction of CEBAF and RHIC were very different; however, these new facilities have catalyzed the emergence of a broad high-energy nuclear physics community that is now largely unified in its focus on the goal of understanding strong interactions at the partonic level—a goal that ensures many scientific points of contact between the two facilities.

The main accelerator at Brookhaven's *Relativistic Heavy Ion Collider (RHIC)* consists of two intertwined rings of superconducting dipole and quadrupole magnets. The rings are 3.8 km in circumference and have six intersection points, four of which are instrumented for nuclear physics experiments. RHIC is capable of producing heavy-ion collisions at center-of-mass energies as high as 200 GeV per nucleon pair for the heaviest nuclei, and proton-proton (*pp*) collisions at center-of-mass energies up to 500 GeV. The anticipated luminosities are 2×10^{26} cm^{-2} s^{-1} for gold-gold collisions and up to 2×10^{31} cm^{-2} s^{-1} for *pp* collisions. During production running, the tandem/booster/AGS complex is used to fill the rings about twice each day. Protons can be polarized either longitudinally or transversely. Both the heavy-ion and the polarized-proton capabilities are unique worldwide.

The commissioning of the RHIC accelerators and detectors started in the first quarter of 2000 and progressed with great success throughout the year. The first collisions of gold ions at 65 + 65 GeV per nucleon were achieved in June 2000, and about 1 μb^{-1} integrated luminosity per experiment was delivered during this commissioning run. The 2001 gold-gold run delivered more than 50 μb^{-1} integrated luminosity per experiment. Near-term luminosity upgrades will bring the integrated luminosity values to 2–4 nb^{-1} for the same period, with further planned upgrades adding another factor of ten. The complex has now reached 100 GeV per nucleon for gold ions in both rings, with collisions observed in all four detectors and more than two dozen papers accepted for publication. Commissioning associated with the RHIC spin program has also been impressive, with collisions achieved with polarized protons at 100 + 100 GeV for all four experiments, and luminosities above 10^{30} cm^{-2} s^{-1} reached after only two months of commissioning. Operation of the Siberian Snake with high-energy beam to preserve and control the proton spin direction during acceleration and storage is now routine. The polarized-proton part of the RHIC program will operate during about 10 weeks of the planned 30 weeks of scheduled operation per year.

The *Alternating Gradient Synchrotron (AGS)* at Brookhaven has become the injector for RHIC. However, since the RHIC rings require only two or three fills each day, the AGS remains available to provide a proton beam during RHIC operation, up to 20 hours per day. The cost of the fixed-target program is reduced to the costs associated with the fixed-target beamlines, plus the incremental cost of running the AGS during the periods it would otherwise be kept in an idle state. This mode of running was initiated during the 2001 running period.

The *Continuous Electron Beam Accelerator Facility (CEBAF)* at Jefferson Lab was commissioned just after the 1996 long-range plan was developed. CEBAF has been a resounding success, matching or exceeding all design specifications. CEBAF is a superconducting, continuous-wave accelerator with a maximum energy of 5.7 GeV and a 100% duty factor. The racetrack-shaped accelerator 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 with different energies to three experimental areas. Three distinct beams with 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 and likely to remain so for some time. 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 10^{-4}, 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 with polarization in excess of 75% at currents exceeding 100 μA. These beams have minimal helicity-correlated variations of beam parameters, making them ideally suited for precision experiments on parity violation. The polarized electron beam is now used routinely for all experiments.

The *Bates Linear Accelerator Center* at MIT provides high-quality electron beams at energies up to 1 GeV. The pulsed linac and the isochronous recirculator provide currents in excess of 50 μA at a duty factor of up to 1%. The accelerator-recirculator system feeds the recently completed South Hall Ring (SHR). This 190-m-circumference ring operates at peak circulating currents of up to 200 mA for internal target experiments and extracted currents of up to 10 μA with duty factors of about 85%. The facility has two experimental halls, in addition to the internal target area in the SHR. In the North Hall, the SAMPLE experiment is investigating the electroweak structure of the proton at low energies. The South Hall contains the medium-resolution OHIPS magnetic spectrometer, as well as a newly commissioned out-of-plane system of magnetic spectrometers (OOPS). Construction of a major new detector, the Bates Large Acceptance Spectrometer Toroid (BLAST), has been completed, and commissioning will begin in 2002. The initial BLAST program is expected to run through 2005. In addition, one experiment each year with the OHIPS/OOPS system is planned after 2002.

Nuclear structure and nuclear astrophysics facilities. Four low- and intermediate-energy heavy-ion accelerator facilities currently operate as national user facilities. The primary physics focus of these machines, as well as eight smaller university-based facilities, is the study of nuclear structure and nuclear astrophysics.

The *National Superconducting Cyclotron Laboratory (NSCL)* at Michigan State University is the premier intermediate-energy heavy-ion user facility in North America. Citing the compelling scientific opportunities to be made available with beams of rare isotopes, the 1996 long-range plan included the immediate upgrade of NSCL among the highest priorities for new construction. This upgrade of NSCL is now complete, and the new coupled cyclotron facility has begun operations. The coupled cyclotron facility will be the leading facility for in-flight radioactive-beam physics in North America until RIA is available. It will provide large gains in the intensity of intermediate-energy primary beams, compared with the stand-alone K1200 cyclotron. For very heavy ions ($A > 150$), it will also provide a significant increase in energy. This gain in primary beam intensity, together with the increased acceptance of the new A1900 fragment separator, will provide intensity increases of 100- to 10,000-fold for most fast beams of rare isotopes.

The upgraded NSCL will lay the groundwork for a significant part of the RIA scientific program, and it will contribute to the development of techniques and hardware for RIA. For example, the large-area neutron and charged-particle detector arrays now being developed at NSCL will be well suited for use at RIA. In addition, NSCL has, for many years, played a major role in training nuclear and accelerator scientists; this role is an essential element in the preparation for RIA.

The *Argonne Tandem-Linac Accelerator System (ATLAS)* consists of a superconducting linear accelerator that is injected by either a 9-MV tandem Van de Graaff or a superconducting positive-ion injector. The facility produces beams of nuclei from hydrogen through uranium with maximum energies from 20 MeV per nucleon for light nuclei to 10 MeV per nucleon for the heaviest, at currents ranging from several particle-microamps for light projectiles to hundreds of particle-nanoamps for heavier elements. The accelerator has excellent energy and time resolution (10^{-3} or better and as good as 100 ps, respectively). Over the past five years, in response to the increased interest in physics at the limits of stability, the capability of producing and accelerating exotic beams has been developed. Beams of ^{8}B, ^{17,18}F, ^{21}Na, ^{25}Al, ^{44}Ti, and ^{56}Ni have been used for research, with intensities on target of about 5×10^{6} s^{-1}. The facility is equipped with state-of-the-art instrumentation required for a broad-based research program in nuclear structure, nuclear astrophysics, reaction dynamics, and fundamental interactions. Major equipment includes the Fragment Mass Analyzer, two magnetic spectrographs, a multidetector gamma-ray facility, and a precision Penning trap. Transfer of fusion products into the trap is done with a fast gas-catcher cell that has demonstrated high efficiency and chemical independence. Such a cell is at the core of the RIA concept. As a national user facility, ATLAS hosts large instruments, such as Gammasphere or the Oak Ridge–Texas A&M–Michigan State BaF_2 array, which exploit both the unique characteristics of the machine and the capabilities offered by coupling these devices to other instruments available at ATLAS. The recent, very successful campaign with Gammasphere coupled to the Fragment Mass Analyzer is a good example.

The *88-Inch Cyclotron* at Berkeley Lab supports a wide range of low-energy nuclear science for a large international community of users. The central component is a sector-focused, variable-energy cyclotron that can be fed by either of two electron cyclotron resonance (ECR) ion sources. This versatile combination produces heavy-ion beams of elements throughout the periodic table. For helium to oxygen, beam energies are as high as 32 MeV per nucleon; the maximum energy decreases with increasing mass, reaching 5 MeV per nucleon at bismuth. Light ions are available at intensities of 20 particle-microamps. The unique combination of high-intensity stable beams, such as ^{51}V, ^{64}Ni, and ^{86}Kr, and the high-efficiency Berkeley Gas-filled Separator (BGS) are essential for the production and detection of new superheavy elements. Gammasphere, the world's most powerful instrument for detecting low-energy gamma rays, is currently in full operation at the 88-Inch, serving a large, active user community for a broad range of physics studies, including nuclear structure studies and fundamental symmetry tests. Radioactive beams are also being developed, including ^{11}C beams with world-record intensities up to about 10^{8} s^{-1} on target. Berkeley scientists have made crucial contributions to the present generation of instrumentation, including advanced ECR ion sources, Gammasphere, the BGS, and the Facility for Exotic Atom Trapping. VENUS, a next-generation ECR ion source now under construction at Berkeley Lab, will greatly extend the scientific reach of the present 88-Inch research program by providing ion beams as heavy as uranium at energies at or above 5 MeV per nucleon. VENUS will also serve as the prototype ion source for RIA's high-intensity heavy-ion driver linac.

The *Holifield Radioactive Ion Beam Facility (HRIBF)* is a first-generation radioactive-ion-beam facility developed to make use of existing accelerators at Oak Ridge. Radioactive species are produced by intense light-ion beams from the Oak Ridge Isochronous Cyclotron and postaccelerated by the 25-MV tandem electrostatic accelerator. The radioactive-ion-beam injector system, consisting of a high-voltage platform on which the production target and beam preparation and purification hardware reside, links production and postacceleration. The suite of radioactive beams available for research is expanding rapidly. Experiments have included high-profile nuclear astrophysics and reaction physics experiments using $^{17,18}F$ beams and a successful campaign of nuclear structure studies using a variety of neutron-rich beams. HRIBF is currently the only facility in the world capable of providing reaccelerated beams of medium-mass neutron-rich radioactive ion beams. This capability will remain unique for several years. HRIBF has made significant contributions to the technology of producing radioactive ion beams, including innovative ion sources and highly effective production targets. A great strength of the facility is the suite of state-of-the-art experimental equipment optimized for radioactive-ion-beam experiments, including two recoil separators, a gas-filled spectrograph, the CLARION gamma-ray array, the HYBALL charged-particle detector array, silicon-strip arrays, specialized detectors and electronics for decay studies, and detectors to monitor and help tune low-intensity radioactive ion beams. Many existing and planned experimental tools have direct application for future research at RIA. Similarly, HRIBF will play a key role in manpower development and training for radioactive-beam research based on ISOL (isotope separation on-line) technologies, while RIA is being developed and brought on-line.

The federally supported university accelerator facilities at Florida State, Notre Dame, SUNY Stony Brook, Texas A&M, TUNL (Duke), Yale, and the University of Washington constitute a very productive component of the national program. These facilities are primary locations for attracting and educating the undergraduate, graduate, and postgraduate students who will form the next generation of nuclear scientists. These facilities are extremely cost-effective. Operating funds are relatively modest, and federal investments are matched by very significant investments by the universities.

The accelerators at these university-based facilities deliver a wide variety of light- to heavy-ion beams, ranging in energy from a few MeV per nucleon to 80 MeV per nucleon. A diverse array of detectors, high-performance spectrometers, and special-purpose beamlines, specifically designed to match accelerator capabilities, is also in place. Essential, innovative, high-risk research on nuclear structure, nuclear astrophysics, nuclear dynamics, fundamental interactions, and applications of nuclear techniques is carried out at the university facilities. Significant radioactive-beam capabilities have been developed at Notre Dame and Texas A&M. New efforts for pursuing low-energy studies of astrophysical interest have been initiated at Notre Dame and TUNL. The use of polarized beams for experiments in nuclear astrophysics represents a fascinating new development. Complementary techniques and ideas for nuclear astrophysics experiments have been developed and are being pursued at Texas A&M, TUNL, Yale, and the University of Washington. Strong programs in nuclear structure are pursued at Florida State, Notre Dame, Texas A&M, TUNL, and Yale, using a broad and complementary variety of instrumentation.

Two neutron-beam facilities in the U.S. also have ongoing nuclear science programs. They are the *Oak Ridge Electron Linear Accelerator (ORELA)* and the *Los Alamos Neutron Science Center (LANSCE)*, now operated by the DOE Office of Defense Programs. These facilities employ high-intensity pulsed neutron beams with time-of-flight analysis. The neutron flux at ORELA, created through (γ,n) reactions by an electron beam of about 150 MeV on heavy target material, is used for nuclear astrophysics measurements. Neutrons at LANSCE are generated by proton-induced spallation and provide high-intensity fluxes of pulsed neutrons from 10^{-8} eV to 800 MeV. These neutron beams are used to carry out tests of fundamental symmetries and to pursue research on nuclear structure and reactions, in addition to roles in other fields, including materials science and stockpile stewardship.

Other facilities. *The Indiana University Cyclotron Facility (IUCF)* is a medium-energy nuclear physics user facility based on an electron-cooled storage ring (the

Cooler) that receives beam from a new synchrotron injector system. It is now the only facility in the U.S. that can provide users with proton and deuteron beams in the energy range from 100 to 500 MeV. IUCF has produced a number of technical achievements in the past five years. The Cooler Injector Synchrotron and the Polarized Ion Source were completed and commissioned, yielding about a hundredfold increase in the stored beam intensity in the Cooler ring and resulting in much more reliable operation. Currents of up to 10 mA of unpolarized proton beam and up to 2.5 mA of 70% polarized beam are now available. A laser-driven polarized gaseous target was developed and installed in the Cooler ring. First data have also been taken with the newly commissioned Polarized Internal Target Experiments.

Nuclear physics research programs with significant U.S. support are also carried out at several facilities operated primarily to pursue studies in other fields of physics. One such facility is the *High Intensity γ-Ray Source (HIγS)* at the Duke University Free Electron Laser Laboratory. The storage-ring free electron laser (FEL) is used to produce a high-intensity (in excess of 10^7 photons s^{-1} MeV^{-1}) gamma-ray beam in the energy range from 2 to 225 MeV by intracavity Compton backscattering. The energy resolution and intensity of the gamma-ray beam is determined by collimation. The gamma rays are nearly 100% linearly polarized.

The *End Station A Facility (ESA)* at SLAC has carried out fixed-target electron-scattering experiments for more than 30 years. ESA operates with electron energies in the range 15–48 GeV, with between 1×10^9 and 5×10^{11} electrons per pulse and 120 pulses per second. It remains a unique facility for probing QCD in the nucleon, especially when high beam polarization, coupled with a beam energy greater than 15 GeV, is needed. Experiments at ESA have produced some of the world's most precise data on the structure of the nucleon. The E158 experiment, which is now under way, will make the world's most precise measurement of the electroweak mixing angle at low Q^2 (see pages 74–75) via parity-violating Møller scattering. Upon completion of E158, a new program of polarized-photon experiments will be commissioned that will study novel aspects of nuclei and nucleons that can only be probed with high-energy polarized photon beams.

The *Laser Electron Gamma Source (LEGS)* is a facility at the National Synchrotron Light Source at Brookhaven. Gamma-ray beams are produced by Compton backscattering of laser light from electrons circulating in the 2.5- to 2.8-GeV X-Ray Ring. Fluxes of up to 10^7 photons s^{-1} are obtained. Photons are tagged (with 100% efficiency) by detecting the scattered electrons in a spectrometer incorporated into the storage ring. The maximum gamma-ray energy available at the facility is 470 MeV, with linear and circular polarization of >75% available. The facility has an assortment of detector systems, including a medium-energy gamma spectrometer and a 1.5-m^2 24-element phoswich scintillator array for time-of-flight measurements.

Collecting the Evidence: Major Detectors for Nuclear Physics

The development of powerful instrumentation to address the questions that drive the field is an integral part of the enterprise of nuclear science. In addition to the major detector systems discussed here, there have been substantial developments in smaller-scale instrumentation since the 1996 long-range plan, many of which are mentioned briefly in the facility descriptions in the previous section.

Neutrino detectors. It is difficult to exaggerate the impact on nuclear physics of recent results obtained from large underground detectors designed to study neutrino astrophysics. The glimpse that has already been provided of physics beyond the Standard Model may be the beginning of a major intellectual revolution in physics. The most compelling recent results come from two experiments based on large water-Cerenkov detectors, both outside the U.S. but with significant U.S. participation. All such detectors must be large, because the probability of a neutrino interacting with matter is exceedingly small. For the same reason, such detectors must be carefully constructed to reduce background from radioactivity and cosmic rays.

SuperKamiokande, a Japan-U.S. collaboration located 1000 m underground in the Kamioka mine in Japan, is a water-Cerenkov detector consisting of 50,000 tons of water enclosed in a tank 40 m in diameter and 40 m high, viewed by 13,000 phototubes. The Sudbury Neutrino Observatory (SNO), a Canada-U.K.-U.S. collaboration, is also a water-Cerenkov detector (shown on page 78), located 2000 m underground in the Creighton mine in Canada. Unlike SuperKamiokande, SNO also contains about 1000 tons of heavy water, allowing it to distinguish electron neutrinos from other neutrino flavors by taking advantage of neutrino interactions with deuterium nuclei. A new solar neutrino detector, Borexino, which will be sensitive to low-energy (<1 MeV) neutrinos, is now being brought on-line by an Italian, German, Russian, and U.S. collaboration in the Gran Sasso underground laboratory in Italy. It is worth pointing out that no deep underground experiment is currently operating in the U.S., although deep underground neutrino observatories originated with the pioneering Ar-Cl experiments in the Homestake mine in South Dakota.

Even though neutrino oscillations have now been demonstrated, much work remains to be done to sort out possible neutrino-mass scenarios and to establish absolute masses. Oscillation experiments on neutrinos of terrestrial origin, such as the MiniBooNE experiment at Fermilab, shown in Figure 3.1, and the KamLAND experiment in Japan, may help with the former problem and may address the question of whether sterile neutrinos exist, as suggested by the results of the LSND experiment at Los Alamos. However, high-precision beta-endpoint measurements or a new generation of double-beta-decay experiments will be required to directly determine the masses.

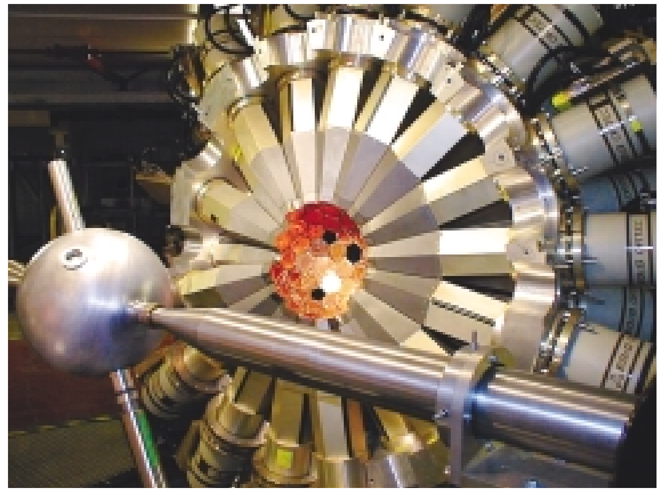


Figure 3.2. Half a Gammasphere. In normal use, two hemispheres of germanium crystals, surrounded by bismuth germinate scintillator shields, are joined to form a complete sphere around the target chamber (shown in the foreground). Gammasphere was built by a collaboration of national laboratories and universities and has been in use in its fully implemented form since July 1996. Gammasphere, now at Berkeley Lab's 88-Inch Cyclotron, is currently the world's premier low-energy (0.05 to 5 MeV) gamma-ray detector facility.

Detectors for nuclear structure and nuclear astrophysics. The Gammasphere photon detector, shown in Figure 3.2, consists of an array of 110 large Compton-suppressed germanium crystals. It has a very high efficiency and high energy resolution for gamma rays in the energy range from 50 keV to about 5 MeV. Since its dedication in December 1995, it has been operated as a National Gamma-Ray Facility at Berkeley Lab's 88-Inch Cyclotron and at Argonne's ATLAS facility. In conjunction with auxiliary x-ray, charged-particle, and neutron detectors, this premier instrument has been used to explore many novel phenomena at high spins and in nuclei far from stability.

Studies of nuclei far from stability require powerful recoil separators that are capable of tagging reaction products produced with microbarn to picobarn cross sections. Three such separators are currently operational at Argonne (Fragment Mass Analyzer), Berkeley Lab (Berkeley Gas-

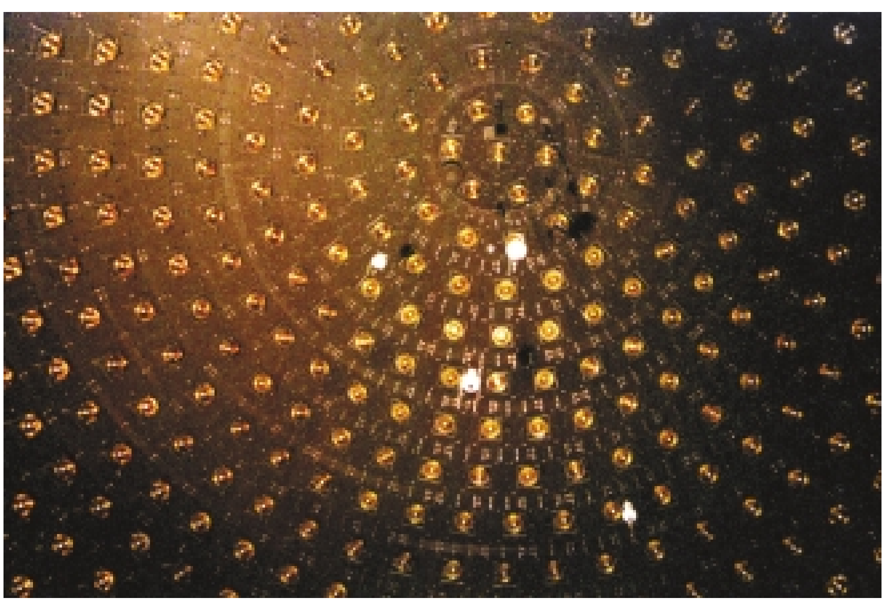


Figure 3.1. Tapping Fermilab's neutrinos. The MiniBooNE experiment at Fermilab takes advantage of an intense beam of muon antineutrinos produced by the 8-GeV proton beam available there, in an attempt to confirm or refute an observation of neutrino transformations reported by the LSND experiment at Los Alamos. The neutrino detector for the MiniBooNE experiment consists of a 12-m-diameter steel sphere containing 800 tons of pure mineral oil, viewed by 1500 photomultipliers, some of which can be seen here.

Figure 3.3. Reflections of the next generation. The Large Area Silicon Strip Array (LASSA) at NSCL reflects the images of several graduate and undergraduate students who were involved in its design and construction. The detector array comprises nine telescopes, each of which consists of a thin, 65-μm silicon-strip detector, followed by a thick, 1.5-mm silicon-strip detector, backed by four 6-cm-long CsI detectors. This detector is a working prototype for the next generation of experimental devices for use with rare isotope beams.

filled Separator), and Oak Ridge (Recoil Mass Spectrometer, RMS). The RMS is equipped with many specialized auxiliary detectors that make it ideally suited for nuclear structure studies with radioactive ion beams.

An aggressive program of instrumentation development is under way for the new coupled cyclotron facility at NSCL. Major equipment under development includes a segmented germanium array, a high-granularity silicon-strip-CsI array (shown in Figure 3.3), a sweeper magnet, a Penning trap, and a high-energy neutron wall. A superconducting magnetic spectrometer (S800) that will take advantage of the capabilities of the new facility has already been commissioned. The S800 is a large-solid-angle (10–20 msr), large-momentum-acceptance, high-resolution ($\delta E/E \cong 10^{-4}$) spectrograph.

Detectors for exploring the quark structure of matter. At CEBAF three experimental areas, Halls A, B, and C, contain complementary equipment capable of supporting experiments that probe a wide range of physics.

Hall A is the largest of the three CEBAF experimental areas. The primary base equipment comprises two 4-GeV/c high-resolution superconducting magnetic spectrometers (HRSs), capable of a momentum resolution of 10^{-4} in a solid angle of 8 msr and a 10% momentum range. The detector packages have been optimized differently: one for detecting electrons and another for detecting hadrons. The hadron spectrometer is equipped with a focal-plane polarimeter.

Hall B is equipped with the CEBAF Large Acceptance Spectrometer (CLAS) and a bremsstrahlung tagging system. CLAS is based on a toroidal magnetic field produced by six superconducting coils. The six sectors between the coils are instrumented with drift chambers, Cerenkov counters, scintillation hodoscopes, and electromagnetic calorimeters, which identify and determine the momentum of several simultaneously emitted charged particles. CLAS combines large-solid-angle acceptance with excellent particle tracking, identification, and momentum resolution. Together with the bremsstrahlung tagging system, the CLAS facility provides special capabilities for studying the structure of nucleons by electro- and photoexcitation.

Hall C, illustrated in Figure 3.4, supports a broad research program, including the study of strange matter, parity-violation measurements, and high-Q^2 form-factor measurements. This varied program requires a flexible set of instrumentation. The primary base equipment in the hall consists of a superconducting medium-resolution (10^{-3}), high-momentum (up to 7 GeV/c) magnetic spectrometer (HMS) and a short-orbit magnetic spectrometer (SOS). The HMS serves as a hadron spectrometer for high-Q^2 measurements and as an electron spectrometer both for inclusive scattering experiments and for coincidence experiments in combination with the SOS. The SOS is a normal-conducting quadrupole-dipole-dipole spectrometer with a maximum central momentum of 1.5 GeV/c and a short path length, permitting efficient detection of short-lived particles.

Detectors at RHIC: Probing hot, dense matter. The attempt to observe phase transitions in bulk nuclear matter by colliding two heavy nuclei at RHIC requires detectors covering the full solid angle, having large dynamic ranges, and, at the highest energies, able to handle the highest particle densities emerging from any reaction studied in the labo-

Figure 3.4. Hall C at CEBAF. The photograph was taken along the beam delivery direction and shows the short-orbit spectrometer (SOS) on the left and the high-momentum spectrometer (HMS) on the right. The HMS can serve as a hadron spectrometer for high-momentum-transfer form-factor measurements and as an electron spectrometer for inclusive scattering experiments. It can also be used together with the SOS for coincidence experiments. The SOS is optimized to detect short-lived particles before they decay.

ratory. The RHIC detectors, two of which are shown in Figure 3.5, collectively cover all of the predicted signatures for the quark-gluon plasma. Two complementary major detector systems, PHENIX and STAR, and two smaller-scale detector systems, PHOBOS and BRAHMS, were operating during the first run of RHIC in summer 2000, when ^{197}Au beams were collided at 65 + 65 GeV per nucleon. Several hundred thousand instrumented detector channels are not uncommon in these detectors. All four detector collaborations have published initial physics results from their first data, and all four have completed a first data run with gold-gold collisions at 100 + 100 GeV per nucleon, as well as a run with polarized protons at 100 + 100 GeV.

The PHENIX detector focuses on the detection of leptons, photons, and hadrons in selected solid angles, with a high event-rate capability and operation of several simultaneous rare-event triggers, to emphasize the electromagnetic signatures of quark-gluon plasma formation. The central part of PHENIX consists of an axial-field magnet and two detector arms, each covering one-fourth of the full azimuth. Each arm is equipped with a multisampling drift chamber, pad chambers giving 3-D space points, a gas-filled ring-imaging Cerenkov (RICH) counter tuned for electron identification, time-of-flight arrays, and finely segmented electromagnetic calorimeters. Silicon detectors close to the beam pipe provide nearly full-solid-angle coverage for particle detection. Two muon arms, which include a lampshade magnet, cathode-strip tracking chambers, and a muon identifier with about 1000 tons of steel, have been added for use in the heavy-ion and spin programs. Upgrade items proposed for PHENIX include a hadron-blind inner electron detector for low-mass pairs and Cerenkov counters for high-momentum hadron identification.

The STAR detector uses the large-solid-angle tracking and particle identification capabilities of a cylindrical time-projection chamber, placed in a large solenoidal magnet. The design emphasizes detection of the global features of the hadrons and jets as the signatures for quark-gluon plasma formation. Charged hadrons may be identified over the full azimuth and two units of pseudo-rapidity. Recent additions to this detector include a silicon vertex tracker, a time-of-flight array, a RICH tuned for high-momentum hadron identification, and a pair of forward time-projection chambers. An electromagnetic calorimeter with both a central barrel and one endcap is being added for use in the heavy-ion and polarized-proton programs.

PHOBOS is a small detector, which focuses on hadronic signatures for the quark-gluon plasma at low transverse momentum. Its double-arm spectrometers use compact magnets with strong magnetic fields and high-spatial-reso-

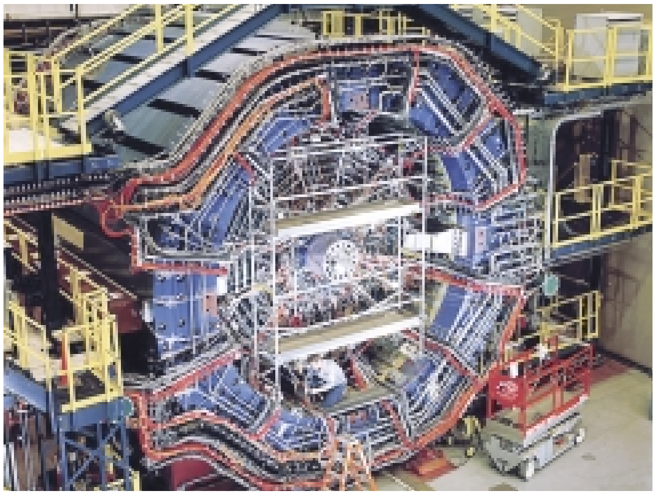


Figure 3.5. Detectors at RHIC. RHIC is currently instrumented with four detectors, two major ones (STAR and PHENIX) and two smaller ones (BRAHMS and PHOBOS). STAR, on the left, is a large-acceptance detector built around a central time-projection chamber (TPC) in a solenoidal magnetic field. Inside the TPC is a silicon vertex tracker for detecting secondary vertices. One of the smaller detectors, BRAHMS, is shown on the right; it specializes in measuring the fragmentation region of the collisions. Not shown are the PHENIX detector, which is composed of four spectrometers optimized for detecting and identifying electrons, muons, photons, and hadrons, and PHOBOS, the second of the smaller detectors, which is optimized for large event rates.

lution silicon detector planes, including some 80,000 channels of silicon strips. Time-of-flight arrays have been added for particle identification. BRAHMS uses two independent magnetic spectrometer arms for inclusive measurements, with particle identification and the ability to reach from 90 degrees to very forward angles. Particles are identified using time-of-flight, RICH, and time-projection chamber detector packages, together with drift-chamber arrays for precise tracking.

Accelerator Technology

Ion sources. Electron cyclotron resonance (ECR) ion source development continues to play a vital role in improving the performance of existing heavy-ion accelerators and will be crucial for future radioactive-beam accelerators such as RIA. New high-performance ECR ion sources based on the 14-GHz AECR-U developed at Berkeley Lab are now in operation on the ATLAS linac at Argonne and the coupled cyclotrons at NSCL. Recent experiments at the Laboratory for Nuclear Science in Italy have demonstrated that increasing the RF frequency to 28 GHz quadruples the intensities of high-charge-state ions. VENUS, an ultrahigh-field superconducting ECR ion source specifically designed to operate at 28 GHz, will begin test operation at Berkeley Lab in early 2002.

Since the 1996 long-range plan, dramatic progress has been made in the development of sources for radioactive ions. For example, development of robust, efficient ion sources and targets has advanced the production of radioactive ion beams at HRIBF. Target systems are designed to have high porosity and to minimize diffusion times, taking advantage of new materials, such as a matrix of refractory hafnium oxide fibers for production of radioactive fluorine isotopes, and thin layers of uranium carbide deposited onto a rigid, glassy carbon matrix for production of neutron-rich radioactive beams. These developments are enhanced by ion source developments such as the novel Kinetic Ejection Negative Ion Source, characterized by low emittance, low susceptibility to radiation damage, and high efficiency for producing negative halide ions.

Progress on ISOL-type targets capable of handling the large beam current that will be available at RIA has been equally impressive, with the demonstration of refractory metal targets capable of handling more than 40 μA of high-energy protons at the Isotope Separator and Accelerator facility at TRIUMF and two-step neutron generator targets for fission products at Argonne. A new paradigm has emerged for the production of low-energy radioactive beams, with the use of in-flight separation of nuclides, together with a gas-catcher system to capture singly charged ions of reaction products and to deliver them as a low-energy ion beam available for postacceleration. This fast and highly efficient technique is not hampered by the chemical limitations of standard ISOL techniques and has been proposed as the principal technology for the RIA facility.

The direct-current photocathode source of polarized electrons at Jefferson Lab has provided an unprecedented capability for helicity-correlated nuclear physics experiments. An upgraded design promises average currents of 10 mA and higher and will be directly relevant to future energy-recovery linacs as the sources of choice for either electron-ion colliders or next-generation synchrotron radiation x-ray sources of the highest feasible brightness.

Neutron sources have also made significant progress with the development at Los Alamos of an ultracold neutron source obtained from the down-scattering of cold neutrons in solid deuterium at liquid helium temperature. Ultracold neutron densities of the order of 100 cm^{-3} have been obtained. Because such neutrons can be easily contained and polarized, this capability opens interesting new avenues of research.

Acceleration structures and accelerator designs. The intense accelerator-related activities that have been pursued since the 1996 long-range plan, including the commissioning of RHIC, the preparation for RIA and the CEBAF upgrade, and the construction of the Spallation Neutron Source (SNS) accelerator, have led to significant advances in accelerator technology. The following paragraphs summarize developments in five significant areas:

- Superconducting cavity development
- Multiple-charge-state acceleration
- RFQ development
- Energy-recovery linacs
- Superconducting magnet development

For electrons at velocities close to the speed of light, the electropolished cavities tested at Jefferson Lab have achieved gradients up to 19 MV/m at a quality factor of 10^{10}. This advanced technology will be the basis of both the CEBAF upgrade and the driver linac for RIA. The driver accelerator for RIA will require the development of superconducting cavities for velocities between $\beta = 0.02$ and $\beta = 0.7$. Low-velocity ($\beta < 0.2$) and high-velocity ($\beta = 1$) cavities have been developed previously. In this regard, the participation of Jefferson Lab in building the 1-GeV superconducting RF linac for the SNS has been beneficial to both the nuclear science and materials science communities. The SNS is pioneering the kind of large-scale integration of superconducting RF systems that will be needed for future nuclear physics facilities such as RIA. The Jefferson Lab efforts there will provide superconducting elliptical cavities, with $\beta = 0.61$ and $\beta = 0.81$, appropriate for RIA. To meet the remaining needs, a collaboration between NSCL and Jefferson Lab is developing an elliptical superconducting cavity with $\beta = 0.47$, and Argonne is developing a spoke-type cavity with $\beta = 0.39$.

An important breakthrough in the acceleration of high-intensity heavy-ion beams has been achieved with the design of the RIA driver linac, which will use the large acceptance of superconducting cavities to accelerate multiple charge states of these heavy ions simultaneously, eliminating the losses due to charge fractionation associated with stripping stages. This approach, which increases the available current for the heaviest ions by a factor of about 16, has been successfully demonstrated at the ATLAS superconducting linac at Argonne.

Another important component of the RIA facility will be the postaccelerator, which will accelerate the slow radioactive ions from ion source energy to the 0.5- to 10-MeV-per-nucleon energy required for astrophysics and nuclear physics studies. A new low-frequency RFQ structure, based on a split-coaxial design, has been developed to allow the acceleration of singly charged radioactive ions to energies that allow them to be injected into very low-β cavities of the type developed for the positive-ion injector of the ATLAS linac. The split-coaxial RFQ was tested at the Dynamitron facility at Argonne, where it accelerated singly charged xenon ions in CW operation, a feat that increased by almost tenfold the mass-to-charge ratio for ions accelerated in an RFQ in CW operation.

An important new development has emerged for applications requiring high-power electron accelerators such as a free electron laser (FEL), or electron-cooling systems for electron-ion colliders. The ability to recover the unused energy of a high-power electron beam in superconducting cavities has been demonstrated at the Jefferson Lab infrared FEL. This development will result in significant power savings for such facilities.

The superconducting magnet technology for large bending magnets has also advanced significantly, with 14 T now having been achieved in a laboratory setting at Berkeley Lab.

Advanced Computing in Nuclear Physics

Advanced computing has become an essential capability in nuclear physics research, and it will continue to be so for the foreseeable future. The needs for advanced computing technology, techniques, and resources encompass data acquisition and high-level triggers of large detectors, data handling and archiving, off-line processing of experimental data, analysis of massive datasets by hundreds of physicists around the globe, modeling of complex detector systems, and theoretical modeling of complex nuclear systems. These capabilities are provided by major computing facilities that offer the assemblage of hardware and support services that are essential to advancing nuclear science.

Owing to the demand for low latency and high bandwidths, today's large detector data-acquisition systems often exploit advanced computing technology. Examples include the use of interconnects, such as fiber channels (commercially used in large disk arrays), SCI (used in the Cray T3E supercomputer), and myrinet (used in many Beowulf-style parallel computing clusters). Likewise, the storage and data-archiving systems at the large nuclear physics accelerators use the same components as the most advanced supercomputer centers: tape silos from StorageTek and hierarchical storage management software to allow on-demand access to a petabyte of data.

The off-line processing facilities for reduction of the detector data, each consisting of hundreds or thousands of rack-mounted CPUs connected to storage systems with 100 MB s^{-1} networks, operate 24 hours a day to keep up with demand. And yet, as challenging as the various aspects of data handling and data analysis are, the most demanding computational problems occur in numerical modeling. Modeling the response of a real detector to a high-energy heavy-ion collision can take hours of CPU time for a single event, and modeling a single "simple" nuclear system might take 100 years of CPU time.

The computational tools and infrastructure needed by nuclear physicists around the world are similar to those required in other computationally intensive disciplines. This has inspired some researchers in the field to form collaborations with scientists from high-energy physics, earth sciences, combustion research, and biology to address their needs in the context of a data-intensive computational grid, or datagrid. The goal of the datagrid is the robust, reliable, and efficient use of resources, computational and human, across the range of institutions where the scientists work. Although this effort is in its infancy, key partnerships between physical and computational scientists have already formed. We recognize this as a fundamental part of the scientific infrastructure of the 21st century.

Three computing facilities provide significant resources for nuclear physics research, in addition to the numerous facilities dedicated to individual projects. The first of these is the RHIC Computing Facility, which is used jointly by the four experiments (PHENIX, STAR, PHOBOS, and BRAHMS) at RHIC. It provides archiving of the raw detector data, processing of the raw data into summaries suitable for data analysis, and interactive and batch processing resources for physics analysis. As of the end of fiscal year 2001, the capacity for archival storage was 1200 TB, with enough tape drives to achieve a peak bandwidth of 340 MB s^{-1}. There are 65 TB of on-line disk storage, with a peak aggregate bandwidth of 2.2 GB s^{-1}. The facility relies on 1276 Intel processors running the Linux operating system, which achieve an aggregated processing power of ~1 teraflops.

The computer center at Jefferson Lab is used by all of the experiments running at CEBAF. It provides archiving and processing services similar to those at RHIC. At the end of fiscal year 2001, the archival storage system capacity was 600 TB, with tape drives to achieve an aggregate bandwidth of 250 MB s^{-1}. The facility includes 24 TB of on-line disk storage and an Intel Linux processor farm with 350 CPUs.

The National Energy Research Scientific Computing Center (NERSC) at Berkeley Lab is the flagship production computing facility for the DOE Office of Science and is heavily used by nuclear physicists for both experimental and theoretical computations. The massively parallel processing (MPP) and mass storage resources constitute the core of this facility, and allocations are awarded by a competitive proposal process. Nuclear physicists use the MPP resource primarily for a variety of theoretical problems involving numerical modeling, including supernova simulations, lattice QCD calculations, and nuclear structure modeling. In fiscal year 2001, nuclear physicists used 3.1 million processor-hours (390 processor-years), 15% of a total of 21 million hours allocated. For fiscal year 2002, the corresponding number is projected to be 8.5 million (24% of 35 million). The NERSC archival storage system has a capacity of 1300 TB, including legacy data and a tape bandwidth of about 500 MB s^{-1}. For fiscal year 2002, nuclear physicists were awarded one-third of the storage resource.

A recent addition to NERSC (since the previous long-range plan) is an Intel Linux processor farm called PDSF, which is particularly well suited to the needs of experimental physics computations. It is used by a number of nuclear physics experiments, including STAR, SNO, and E895, as well as a number of high-energy physics experiments. It consists of 400 Intel Linux CPUs and 40 TB of on-line disk storage.

Outlook

The past decade has been a remarkable one for nuclear physics. The nation has made very large investments in new facilities and instrumentation, and these facilities have been brought on-line effectively and efficiently, producing results that met the highest expectations. This document offers a roadmap that serves as an equally aggressive agenda for the next decade. The recommendations and other initiatives presented in Chapter 5 provide a good summary of the broad front on which nuclear physics is advancing.

The major initiatives, by the nature of this evolving field, tend to emphasize large projects. While such projects are essential, the importance of innovations in instrumentation developed on a smaller scale must also be remembered. During the period since the 1996 long-range plan, many developments in such areas as ion and atom trapping, atomic mass measurements, and cold and ultracold neutrons, to name a few, have emerged from comparatively small efforts.

And finally, it is crucial that the instrumentation at operating facilities be continually upgraded and improved, to ensure the highest possible scientific return.

4. The Nuclear Science Enterprise

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Education and Outreach

The education of young scientists must be an integral part of any vision of the future of nuclear science, as well as being central to the missions of both the NSF and the DOE. Well-designed educational programs, ensuring a stable supply of nuclear scientists—as well as a scientifically literate society—are essential not only to the fertility of academic research, but also to the needs of medicine, defense, industry, and government. In this section, we analyze the effectiveness and appropriateness of current educational activities in preparing future generations of scientists and in addressing broad educational needs, including diversity issues. We conclude with recommendations on how such activities might be strengthened.

Graduate Education: Preparation for Leadership

Graduate education is at the heart of educational activities in nuclear science. From today's corps of graduate students will emerge the young scientists who will provide tomorrow's intellectual leadership in experimental and theoretical nuclear science, and the talent to help address the needs of the nation in defense, medicine, and industry.

Traditionally, the graduate education of experimentalists has been provided by university-based nuclear laboratories. At such laboratories, graduate students are exposed to and participate in the complete spectrum of activities that characterize experimental nuclear science. They typically play an active role in the design, construction, calibration, and maintenance of experimental equipment, in addition to exploiting these instruments for research. They are actively involved in data-taking, analysis, and interpretation of results. Given the smaller scale of projects at university labs and the less restrictive time constraints, students can develop into true experimentalists, poised to become leaders in the field with a breadth of technical skills and the experience of being part of a team. In addition, the intellectual atmosphere of a university provides exposure to the full range of activities in physics and chemistry, as well as applied areas of research.

Increasingly, however, to realize the breadth of scientific opportunities, experimental nuclear scientists are conducting their research at large centralized facilities, and this trend is expected to continue in the 21st century. As a result, the role of university groups and the nature of graduate education in experimental nuclear science have undergone significant change. Graduate students often begin their careers at a university, taking courses, but then gradually shift their activities to experimental research at one of the large facilities. This shift places new emphasis on the key complementary role that national laboratories play in graduate education and the importance of opportunities for graduate students to be involved in all aspects of experimental research in an atmosphere that addresses the needs of the student. Graduate students in residence at a national facility, under the supervision of the on-site scientific staff, often have major responsibilities for the running of experiments, as well as aspects of the commissioning of apparatus. University groups with sufficient technical resources at their home institutions can also contribute to some of the R&D activities associated with new initiatives, such as detector development, which again provide hands-on training to students early in their graduate careers.

In contrast to the experience of experimentalists, university-based nuclear theory groups are often small, which can limit theory students' exposure to only a part of the full spectrum of ideas and styles in doing nuclear physics. The National Nuclear Physics Summer School—together with more specialized summer schools organized by Jefferson Lab and by Brookhaven—has been developed to complement the opportunities available at a single institution and to facilitate interactions among experimental and theoretical students in all subfields of nuclear science. In these summer schools, students meet not only other graduate students—their future colleagues—but also the leaders of the field, who offer lectures and lead discussions. Also available to theory students is the National Institute of Nuclear Theory, where they can participate in its regular programs.

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

Profiles of a few graduate students appear in "A Graduate Student Gallery," page 100. But these individuals reflect

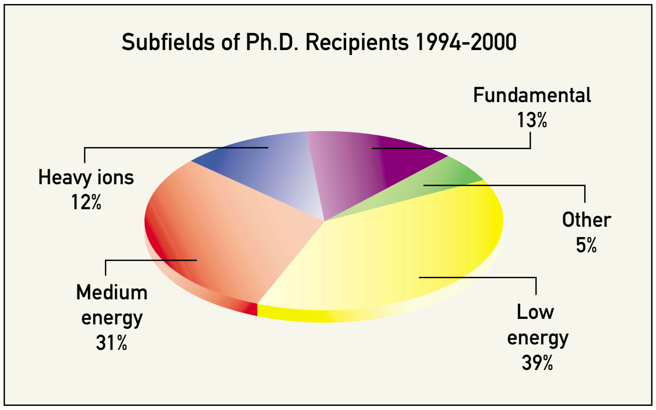


Figure 4.1. Facets of the discipline. The pie chart shows the subfields represented among the nuclear science Ph.D.'s granted in the period 1994–2000.

only a few facets of a multifaceted field. Figure 4.1 provides a more complete picture: a breakdown of nuclear science subfields in which Ph.D.'s were awarded during the period 1994–2000. Each year, about 8% (or over 100) of the Ph.D.'s in physics in the U.S. are awarded in nuclear physics. About 60% of these are supported in part by the DOE, and about 40% by the NSF. About 80% of the Ph.D.'s are awarded to students in experimental nuclear physics, 20% in theoretical nuclear physics. The number of Ph.D.'s in the growth areas of the field—low-energy nuclear structure and astrophysics, intermediate-energy electron and hadron physics, and high-energy heavy-ion nuclear physics—reflects current vitality in these areas. To help realize exciting scientific opportunities of the future, as well as to meet the nation's needs, the nuclear science community will need to enhance its efforts to attract and educate young scientists.

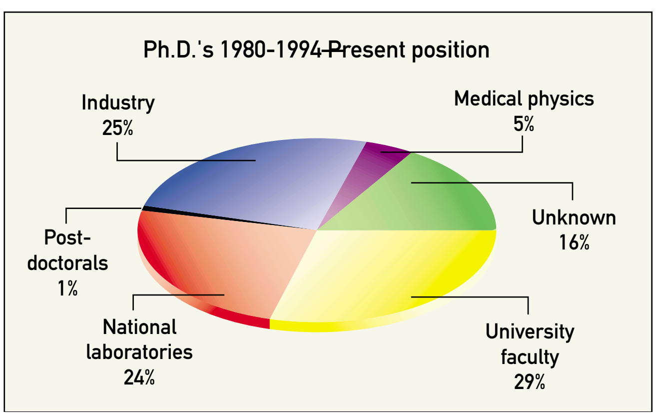


Figure 4.2. Career choices. The pie chart shows the current positions of nuclear science Ph.D. recipients from the period 1980–1994. The results are based on a survey of 19 major universities offering this degree.

Nuclear science has a long tradition of attracting talented young scientists and providing them with the education and training necessary to meet challenges outside their own disciplines. Men and women holding Ph.D.'s in nuclear science have become leaders in industry and finance, innovators in developing medical techniques that rely on nuclear science, and public servants in a host of roles, particularly in national defense. This trend continues. One-half of those who received nuclear science Ph.D.'s between 1980 and 1994 currently pursue careers outside basic research in universities or national laboratories (see Figure 4.2). A few of the paths chosen by former nuclear science graduate students are highlighted in "Career Paths— Nuclear Scientists Contributing to a Productive Nation," page 104.

Undergraduate Education: Introduction to the Excitement of Research

To meet the national need for a citizenry with a strong scientific background, the nuclear science community nurtures the development of future scientists by offering undergraduate students a number of opportunities to experience the excitement of research. Such experiences have proven to be a strong enticement for students to consider pursuing careers in science. Nuclear science research groups and facilities at universities routinely involve bright and eager undergraduate students in their activities, often starting in the freshman year. These students learn modern research techniques and often make significant contributions to the research program. Although a large proportion of these students go on to graduate school, others assume careers in high-school science education.

However, many promising undergraduates attend small colleges that have no ongoing research programs. To provide research experiences for these students, the nuclear science community has benefited greatly from such NSF programs as Research at Undergraduate Institutions (RUI) and Research Experience for Undergraduates (REU), from the DOE-sponsored Energy Research Undergraduate Laboratory Fellowship program, and from summer programs at all of the national laboratories. The Division of Nuclear Chemistry and Technology of the American Chemical Society, in partnership with the DOE, has also supported two summer school programs at San Jose State

A Graduate Student Gallery

Many graduate students gain the bulk of their experience in university laboratories, where they participate in every facet of experimental research. One such laboratory is the Wright Nuclear Structure Laboratory at Yale. The photograph below shows some of the Yale graduate students involved in the commissioning of a new recoil separator, SASSYER. This instrument will be used to study the structure of nuclei beyond lead and approaching the heaviest of elements.

An increasing number of students, however, spend significant time at major national research facilities. In such an environment, the need to gain experience in all facets of research is no less important. Dan Bardayan, for example, spent much of his graduate career in residence at Oak Ridge, working with state-of-the-art instrumentation and collaborating with scientific and technical staff. He played a key role in the installation and commissioning of a recoil spectrograph for radioactive-ion-beam studies and then assumed a leadership role in all aspects of the effort to measure a reaction rate important for nucleosynthesis in nova explosions. He received the 2000 Dissertation Prize in Nuclear Physics from the American Physical Society for this important work.

Sarah Phillips and Allyn Powell, graduate students at the College of William and Mary, are two of the many graduate students around the world involved in the construction of apparatus for the G0 experiment at Jefferson Lab. G0 is a program designed to study the contributions of strange quarks to the proton, using parity-violating electron scattering. The project, led by the University of Illinois, is jointly funded by the DOE and the NSF and involves 14 U.S. universities, Jefferson Lab, and institutions in France and Canada. Jefferson Lab provides infrastructure support and project management, while individual university groups are responsible for developing most of the other experimental components at their home institutions. Such a partnership is cost-effective, as it makes use of local university shops, and it provides hands-on training for graduate students early in their careers, as well as abundant summer intern opportunities for undergraduate students.

Graduate students at the Wright Nuclear Structure Laboratory at Yale, as they participate in the commissioning of the new recoil separator, SASSYER.

Former Yale graduate student Dan Bardayan, working on a recoil spectrometer and silicon detector array at Oak Ridge.

Sarah Phillips and Allyn Powell, graduate students at the College of William and Mary, helping with the construction of one octant of the scintillator detector for the G0 apparatus at Jefferson Lab.

and at Brookhaven, designed to encourage students to pursue careers in nuclear science.

The RUI program has had a direct impact on faculty at undergraduate institutions, enabling them to maintain active research programs and to remain connected with the larger professional community, as well as engaging students during the summer and throughout the school year. The RUI opportunities provide these groups with direct access to facilities and equipment not available in the typical undergraduate institution. Hope College in Michigan is an example of an undergraduate institution where faculty and students have benefited from the RUI program. Undergraduates at Hope help develop instruments and take a lead in data analysis and modeling, in addition to playing active, hands-on roles in the experiments at university and national laboratories (see Figure 4.3).

The nuclear science community has been a leader in sponsoring the REU program, especially at university-based laboratories. This program has been especially successful in engaging women and minorities in undergraduate research. About one-third of the participants are women, and about 10% are nonwhite minorities. The Nuclear Structure Laboratory at Notre Dame, for example, has hosted a particularly successful program for the past 15 years. About ten students participate each year, five with support from the REU program, working in experimental nuclear structure and astrophysics research using stable and radioactive ion beams (see Figure 4.4). Notre Dame also maintains sister relationships with two Historically Black Colleges in Georgia and a Historically Hispanic College in Texas, from which it recruits junior and senior college students. The REU efforts complement programs in which high-school teachers spend the summer participating in a research project, returning in the fall with their students for tours of the facilities and exposure to the research activities.

Figure 4.3. Research at an undergraduate institution. Hope College undergraduate Joe Bychowski works with Professor Paul DeYoung to prepare a light guide and photomultiplier tube for attachment to a long scintillating plastic bar for nuclear reaction studies with radioactive beams. When completed, this component will form part of a large-area wall of detectors.

Figure 4.4. Summer research experience for an undergraduate. Ball State undergraduate Noopur Garg measures the silver content of ancient coins as part of an REU project in applied nuclear physics at Notre Dame.

The new Conference Experience for Undergraduates (CEU) program has been extremely successful in integrating undergraduates from nonresearch institutions, who are doing summer research at host laboratories, into the nuclear science community. The students are supported to attend the Fall meeting of the Division of Nuclear Physics (DNP) of the American Physical Society (APS), where they present the results of their research. About 60–80 students participate each year, about one-third of whom are women (see Figure 4.5) This opportunity is funded by the NSF and the DOE through the national laboratories. In addition to this nuclear science–specific opportunity, undergraduates also participate in the more broadly based interdisciplinary research conferences held on individual campuses.

The nuclear science community also works closely with related physics disciplines and the American Association of Physics Teachers to develop and market undergraduate curriculum materials that reflect 21st century physics and societal problems that science can help address. Recent efforts in physics education reform have developed new materials aimed mostly at introductory physics courses. Such materials are publicized and made broadly available to the community of physics educators.

Figure 4.5. Undergraduates sharing research results. Undergraduate researchers in nuclear science discuss a student poster at the Fall 2000 meeting of the Division of Nuclear Physics, as part of the Conference Experience for Undergraduates program.

Outreach: Fueling the Curiosity of Children and Increasing Scientific Literacy

The technological developments of the future will require an increasingly science-literate and well-informed citizenry. In addition to their roles in undergraduate and graduate student education, the national laboratories, major university laboratories, and many individuals, working alone or as part of interdisciplinary outreach programs, have made significant efforts to enhance the scientific literacy of the public at large and to reach out to K–12 students and teachers.

Representative outreach efforts include the following, which are also illustrated in Figures 4.6 and 4.7:

- CHICOS, a collaborative project involving Caltech, California State Northridge, UC Irvine, and local high-school physics teachers to place an array of particle detectors at high schools in the Los Angeles area. The project offers students in local high schools a unique opportunity to collaborate with university researchers in addressing fundamental issues at the forefront of present-day astrophysics and particle physics. CHICOS and its Seattle-area counterpart, WALTA, are part of the new consortium of North American Large-scale Time-coincidence Arrays (NALTA), which will be extending its program to other parts of North America. See *http://csr.phys.ualberta.ca/nalta/* for more information about NALTA.
- The BEAMS (Being Enthusiastic About Math and Science) program, which brings classes of 6th, 7th, and 8th grade students with their teachers to Jefferson Lab for a one-week modified curriculum. Since 1991 about 15,000 students and 375 teachers have learned science and math from Jefferson Lab engineers and scientists through on-site interactive activities.
- The Nuclear Science Wall Chart and accompanying teacher's guide. This well-disseminated outreach tool (see Figure 4.7) was conceived as an aid to teachers in introducing modern nuclear physics and chemistry into the classroom. It was developed by the Contemporary Physics Education Project, a nonprofit organization of scientists and teachers. To help teachers become comfortable with the chart, they are invited to attend workshops where they are introduced to the basic concepts, participate in hands-on activities, and attend talks by scientists describing their current research activities.
- A program to introduce nuclear science into Navajo schools. This collaboration among Berkeley Lab, Los Alamos, the Glenn T. Seaborg Hall of Science, and Navajo educators and community leaders was prompted by concern among the local population about radiation from old uranium mines near schools serving Navajo students in the Southwest. This collaboration is an outgrowth of the Wall Chart project.
- Facility tours and open houses at most of the major nuclear science laboratories, open to the public.

These specific activities provide only a snapshot. About two-thirds of the nation's nuclear science principal investigators have volunteered their time in efforts to increase public scientific literacy or to bring lively science programs into the K–12 classroom. Such activities have included public "viewing nights" at university telescope facilities, participation in science fairs, discussions with the media, exhibits and publications explaining and popularizing science, and the development of innovative components for the K–12 curricula that bring current research to the classrooms. K–12 school children provide a fertile field where introducing the exciting activities of nuclear science can have a large impact

Linking high-school students to research. Monroe High School students visit Caltech as part of the CHICOS program, in preparation for the installation of a cosmic-ray detector at their school.

Programs for middle-school students. Middle-school students in Virginia visit Jefferson Lab as part of the BEAMS program. Students are seen here weighting down prototype aluminum-foil "boats" during an engineering exercise.

Engaging the public. Graduate student Joann Prisciandaro demonstrates a diffusion cloud chamber to young visitors during an open house at Michigan State's NSCL. The laboratory is host to about 2000 visitors each year.

Outreach to the Navajo nation. New Mexico high school teacher Katie Gilbert solders part of the circuit board for a cosmic-ray detector she built at Berkeley Lab for her school.

Figure 4.6. Outreach to precollege students and the public at large. Outreach efforts include local and regional programs for K–12 students and teachers, preparation of educational materials, and open houses at research facilities.

on children's innate curiosity about the world around them. Through modern information technology, it is now possible to involve many more students in interesting, relevant nuclear science research.

Many scientists and educators also support K–12 education by speaking out on local and state educational issues, particularly the need to increase the quality of K–12 mathematics and science programs in the schools. The Public Information Committee of the DNP of the APS has played an active role in communicating the excitement of nuclear science to members of Congress, the press, and the public.

In an effort to facilitate broad awareness of the plethora of nuclear science activities in education and outreach and to catalyze the development of new programs, the Education Committee of the DNP of the APS has developed the National Nuclear Science and Outreach Database. This searchable database can be found on the Web at *http://NucOutreach.msu.edu/*.

Career Paths—Contributing to a Productive Nation

About one-half of all students who receive Ph.D.'s in nuclear science pursue careers in basic research at universities and national laboratories. However, over half put their training to work in other ways, making contributions equally critical to a productive and creative society.

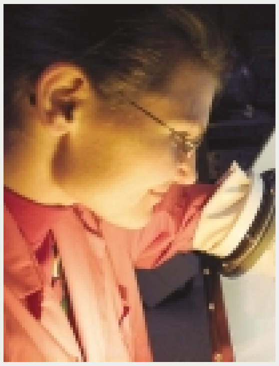
Dr. Kristina Isakovich, Vice-President for Corporate Strategy, Thermo Electron Corporation.

Kristina Isakovich received her Ph.D. from MIT in 1991, helping to develop the techniques for producing polarized electron beams at the Bates accelerator. After receiving her Ph.D., she worked as a physicist at Advanced NMR Systems in an effort to commercialize a high-speed echo-planar MRI imaging system. She then joined McKinsey and Company as a management consultant. In 2000 Isakovich joined Thermo Electron as the Vice-President for Corporate Strategy. Currently, she is playing a key role in reorganizing the corporation to focus on its core business activities in developing instrumentation for life sciences, optical technologies, and a wide array of manufacturing applications.

Dr. Roland Henry, faculty member in the Radiology Department at the University of California Medical Center in San Francisco.

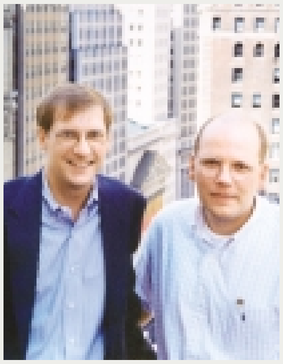
Roland Henry received his Ph.D. in 1992 from Rutgers University, only the second person originally from Belize to receive a Ph.D. in physics. He then pursued his interest in the structure of heavy nuclei as a postdoctoral scholar at Argonne, taking a lead role in some of the first measurements, taken with the current generation of high-efficiency gamma-ray detectors, of highly elongated nuclei. The tools he developed to extract small signals from large backgrounds led naturally to his current position at the Magnetic Resonance Science Center in UC San Francisco's Radiology Department. There he is pioneering new MRI techniques for in vivo studies of metabolism, diffusion, and perfusion in the brain.

Nancy J. Stoyer received her Ph.D. in 1994 in nuclear chemistry from UC Berkeley. During her tenure as a graduate student, she developed an interest in actinide and heavy-element science. In her current position as a staff member at Lawrence Livermore National Laboratory, she is applying her extensive laboratory experience in actinide chemistry to issues of nonproliferation of nuclear materials, a critical component of the nation's security mission. Stoyer is part of the program responsible for monitoring the disposition of highly enriched uranium (HEU) from Russian nuclear weapons. Stoyer participates in teams that monitor Russian facilities where HEU is blended down to reactor-grade material for use in U.S. commercial power plants. She also reviews the documentation received from the Russians and the observations recorded by all of the monitoring teams.



Dr. Nancy Stoyer, examining an actinide sample in a glove box at Lawrence Livermore National Laboratory.

Philip Zecher and Damian Handzy founded Investor Analytics LLC in 1999 to provide analytic services to institutional money managers. Basing their doctoral dissertations on research done at the NSCL, both received their Ph.D.'s in 1995 from Michigan State. Along with their two economist partners, Zecher and Handzy work closely with portfolio managers around the world to better understand the financial risk in the managers' portfolios. After less than two years in business, Investor Analytics has 12 clients and manages 63 portfolios with a total value in excess of $4 billion. Zecher and Handzy feel that their "training as physicists, the analytic skills and the skills to manage large amounts of data that come from working at a major experimental facility, has been one of the cornerstones of our success."



Drs. Philip Zecher and Damian Handzy on the balcony of Investor Analytics LLC, overlooking the New York Stock Exchange.

Expanding Opportunities to a Diverse Population

The nuclear science community is dedicated to including scientists from the full spectrum of backgrounds in all of our activities. To achieve this goal, a wide range of activities has been developed to attract and nurture young scientists from diverse backgrounds. These efforts are particularly important, because, in spite of considerable past effort, women and nonwhite minorities are not yet adequately represented in the nuclear science community. In the future, the community profile is likely to change dramatically, only partly through an influx of foreign students. In 1998, 13% of the physics Ph.D.'s were earned by women and 46% by foreign citizens. About 10% of these degrees were earned by nonwhite U.S. citizens, but only 2% went to African Americans or Hispanic Americans. A survey of DOE and NSF principal investigators in the period 1994–2000 produced a similar profile of nuclear science graduate students: 17% were women, 45% were non-U.S. citizens, and 5.5% were nonwhite U.S. minorities. The future looks more promising in that 24% of undergraduates who participated in nuclear science research were women, and 11% were minorities.

Although the number of women in the profession has grown slightly since publication of the 1996 long-range plan, the number of U.S. minorities, especially African Americans, has not. To change the demographics, specific programs have focused on outreach to African American students at inner-city schools and at Historically Black and Hispanic Colleges and Universities. A new effort has also been launched to bring nuclear science education into the schools of the Navajo Nation, as noted above. The APS Committee on Minorities and the Committee on the Status of Women in Physics sponsor discipline-wide activities, such as luncheons at professional meetings to which undergraduate participants are invited, maintain a speakers bureau of women and minorities, and when invited, visit physics departments and national laboratories and work with them to develop a welcoming climate for all students and faculty, particularly those from underrepresented groups.

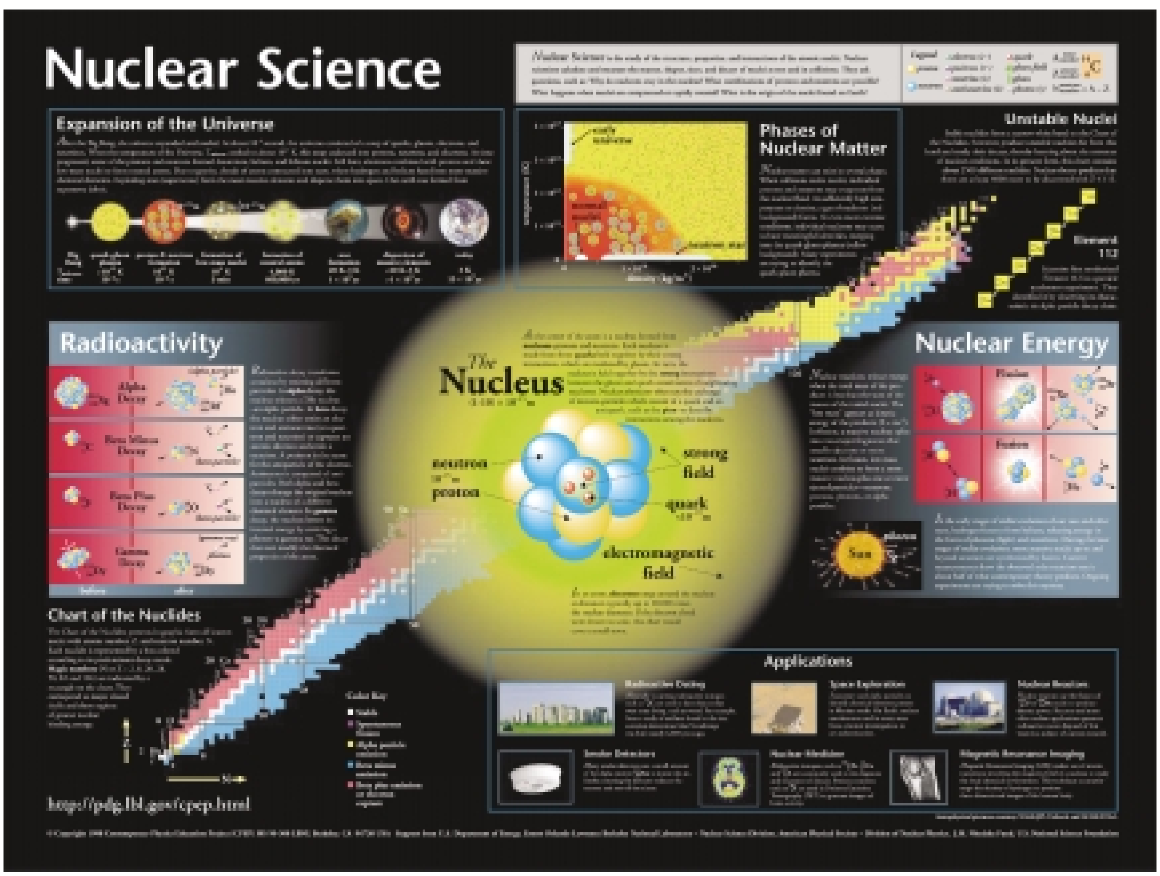


Figure 4.7. The Nuclear Science Wall Chart. This educational aid was prepared by the Contemporary Physics Education Project (www.cpepweb.org), an organization of scientists and teachers. *Reprinted by permission of the CPEP.*

Guiding Principles and Recommendations

- *University-based research groups and laboratories are the lifeblood of our field.* Federal investment in the university infrastructure has traditionally been a major source of funding for science education. Continued federal support, with appropriate matching funds from states and educational institutions, is essential to immerse young scientists in research environments at the scientific frontier and to train future generations of nuclear scientists for basic research and other national roles. Graduate education programs at the universities and at national user facilities must ensure that students acquire the technical and communications skills necessary to prepare them for the full range of career opportunities available for nuclear scientists in basic research and in other areas of national need.

- *Science education and scientific literacy are critical to the future of the nation.* We recognize the value of current educational and outreach efforts by the scientific community and strongly recommend that they be enhanced. Educational and outreach activities catering to K–12 classrooms and to society at large should constitute a strong component of all major institutional research proposals. Both educational and outreach activities should also be more broadly publicized, both to provide models for additional activities and to make the general public more aware of these opportunities. Educational institutions and national laboratories, in partnership with federal funding agencies, should work to identify additional resources for educational and outreach activities.

- *The social diversity of the nation should be reflected in its scientific work force.* Efforts by the scientific community to recruit, train, and retain underrepresented elements of the work force must be increased at all levels of education and in all research activities.

Interdisciplinary Aspects

Over the past decades, most broad disciplines, including physics, have given rise to increasingly specialized subfields. Within physics, these subfields are reflected in funding and even in the structure of professional organizations, such as the American Physical Society. In spite of this compartmentalization, however, strong connections link different subfields of physics. Fostering these interconnections has obvious merit: It will result in more rapid progress in the field overall and greater flexibility in addressing questions of the highest scientific priority.

These connections manifest themselves in more than one way. Most obviously, there are areas of common interest between closely related fields. Nuclear physics, for example, is closely coupled to particle physics and astrophysics. The physics of the neutron and the proton is essentially inseparable from quark physics and quantum chromodynamics (QCD), historically the dominion of high-energy physicists. Likewise, nuclear physics and astrophysics are closely related, though the relationship is rather different. On one hand, nuclear processes govern the evolution of stars, supernovae, and galaxies. Nuclear physics is therefore an important input to understanding this evolution. On the other hand, astrophysical environments, such as neutron stars and supernova explosions, provide unique conditions unattainable on Earth. Experimental observations of these astrophysical objects feed directly into our knowledge of nuclear physics.

A second, and equally important, way in which subfields are connected is through common underlying theoretical techniques and technologies. Many-body theory connects nuclear and condensed-matter physics, and new insights into the collective behavior of interacting particles drive progress in both fields. On the technical side, as in most basic sciences, computers play an increasingly important role in nuclear science. They are used by experimental physicists to collect and analyze large volumes of data, and by theoretical physicists to model the intricate quantal structure of the quark-gluon plasma, hadrons, and nuclei, and to simulate supernovae and the violent collisions of ultrarelativistic nuclei.

It is no exaggeration to say that the connections among these several facets of modern physics are so strong that these fields must progress together. All of them are necessary if we are to obtain a complete picture of the role of the strong interaction in the universe.

Connections to the High-Energy Physics Community

There is currently much overlap between the interests of high-energy and nuclear physicists. These common interests extend from neutrino physics, where both groups are exploring the nature of the electroweak interaction and the question of neutrino mass, to hadronic physics, where they share an interest in nonperturbative QCD and confinement. The National Underground Science Laboratory, a joint proposal that would allow a systematic study of the nature of the neutrinos and their interactions, is discussed on pages 127–129. Here we touch on the common interests in hadronic and QCD physics.

The study of hard partonic interactions and jet physics, which has provided some of the best tests of perturbative QCD, has in the past been considered a facet of high-energy physics. Now this topic is also of fundamental interest in nuclear physics, which addresses issues related to hard scattering in hot and dense partonic environments created in heavy-ion collisions. Both nuclear and particle physicists are actively engaged in studying the possibility of new experiments to probe these issues at RHIC, LHC, and proposed new facilities at DESY and Brookhaven.

The study of the partonic structure of hadrons began with particle physics experiments at SLAC in the late 1960s. Recent studies of the partonic spin structure of the proton, carried out at CERN, SLAC, and DESY, and of the quark and antiquark sea, through muon-pair production at Fermilab, have been key experiments at high-energy laboratories, with much of the intellectual leadership and research effort provided by nuclear physicists.

Likewise, high-precision experiments measuring the strangeness contribution to the nucleon form factor, carried out at Jefferson Lab and at MIT-Bates, have been nuclear physics experiments that touch on a topic of fundamental interest to particle physicists. An outstanding fundamental issue will be addressed by new experiments focused on the gluonic contribution to the proton's spin, which began at RHIC in 2001. Finally, experiments are planned that would study elastic and diffractive scattering at RHIC with polarized protons: These experiments are likely to shed new light on the nature of the pomeron.

High-energy and nuclear physicists also continue to work together in the area of nonperturbative QCD, trying to understand the nature of confinement and chiral symmetry breaking. Lattice QCD has become the primary tool for precise first-principles calculations in nonperturbative QCD, and both nuclear and particle theorists are active in these programs.

Connections to the Astrophysics Community

The interaction between nuclear physics and astrophysics is symbiotic: Astrophysical environments test nuclear physics under extreme conditions, and nuclear physics contributes to what we know about astrophysical phenomena ranging from the beginning of the universe to the end of a star's life. The goals of nuclear astrophysics are to explain the origin of the elements, the properties of matter subjected to extreme temperatures and densities, and the fundamental interactions in the universe.

Nuclear physics played a major role in the development of the standard model of cosmology. The agreement between the observed abundances of light elements and the predictions of primordial nucleosynthesis models, together with the discovery of the microwave background, firmly established the Big Bang as the best model for the evolution of the universe. And models of Big Bang nucleosynthesis (BBN) helped fuel the recent explosion in cosmological discoveries by determining the baryon number density of the universe. Studies currently under way at RHIC will contribute further to our understanding of the phase transition that took place in the first few moments after the Big Bang and that led to the formation of nucleons.

Theories of stellar nucleosynthesis encompass a much wider range of nuclear reactions in order to explain the origin of elements heavier than ^{7}Li. Relevant processes include the basic synthetic cycles present during most of a star's life and the explosive synthesis that occurs as massive stars undergo supernova explosions. Many of the cross sections important in understanding these processes remain to be measured. Such measurements await the construction of RIA, together with theoretical and computational efforts to determine the best way to use RIA for nuclear astrophysics. Explosive nucleosynthesis in novae and supernovae, in particular, remains a conceptual and computational challenge.

Compact remnants of supernovae are the best example of an astrophysical environment that tests nuclear physics under extreme conditions. Neutron stars are strongly magnetized, rapidly rotating, neutron-rich nuclei, with central densities at least twice that of atomic nuclei. The equation of state of such matter has been extensively studied theoretically, and Monte Carlo methods have succeeded in characterizing neutron matter at twice nuclear densities. Strong observational constraints on the equation of state should be attainable with future high-resolution studies of the mass and radii of neutron stars. For example, if neutron stars are found with masses as large as 2.3 solar masses, exotic phases in their cores will be ruled out.

Finally, a major area of overlap among astrophysics, nuclear physics, and particle physics is neutrino physics. In a coordinated effort by the three communities, the first clear evidence of physics beyond the Standard Model has emerged: Neutrinos oscillate and have masses! This joint effort dates back to the solar neutrino problem, a problem in nuclear astrophysics. The future of this field depends on the continued coordination among the three communities involved and the possible construction of a large underground facility.

Nuclear physics, particle physics, and astrophysics provide many opportunities for discovery in cross-disciplinary efforts. The nuclear science community is well placed to seize these opportunities and to lead the effort on a number of intellectually challenging frontiers.

Theoretical Foundations: Many-Body Physics

The nucleus is a quantal many-body system, which shares many features of the many-body systems in atomic and condensed-matter physics. Accordingly, there is a continuous exchange of ideas among physicists studying the various many-body systems. For example, the widely used many-body perturbation theory originated in the work of Brueckner, Bethe, and Goldstone on nuclear matter, whereas the Bardeen-Cooper-Schrieffer theory of superconductivity has now found applications in nuclear structure physics.

Shell models are broadly applicable to various systems, ranging from the quark model of hadrons to nuclei, atoms, quantum dots, and atomic clusters. The shell structures of nuclei and small metallic clusters—sodium clusters, for example—are very closely related. In both systems, deformations occur between magic numbers to reduce the shell energy. The fractional quantum Hall effect observed in two-dimensional conductors in large magnetic fields can also be related to a shell structure.

Another concept shared by physicists studying various many-body systems is that of energy-density functionals, which offer a very efficient way to describe ground-state properties of large nuclei; molecules; mesoscopic systems, such as clusters, quantum dots, and wires; and extended matter.

The collective phenomena exhibited by both nuclei and complex molecules are strongly influenced by their shape and other symmetries. Essentially common methods are used to describe these phenomena in various branches of many-body physics. Another common thread is the phenomenon of superconductivity: An attractive interaction among constituent current-carrying particles gives rise to coherent many-body states of the particles near the Fermi surface. Methods developed by nuclear theorists to treat superfluidity in nuclei have recently been applied to superconducting ultrasmall aluminum grains. Also, the rotational behavior of Bose-Einstein condensates in dilute atomic vapors shows similarities to that of rotating nuclei.

Wigner introduced the concept of the random Hamiltonian matrix to explain the statistical aspects of the many states of highly excited compound nuclei. This concept has now grown into the field of quantum chaos, with applications to quantum dots and other mesoscopic systems. Recently, it has been found that random two-body interactions can generate some of the regularities observed in nuclear spectra. Nuclear, atomic, and condensed-matter physicists also share an interest in quantum Monte Carlo simulations of many-body systems. All subfields face similar challenges, and several researchers in this area have worked on both nuclear and condensed-matter problems. In coming years, nuclear physicists will intensively study rather unusual kinds of matter: the quark-gluon plasma, dense hadronic matter in supernovae and neutron stars, highly magnetized matter in the magnetars, etc. New ideas, such as color flavor-locked superfluidity and mixed "pasta" phases of neutron star crustal matter have originated from these studies. It is not unlikely that some of them will find applications in condensed-matter and other many-body systems.

Technical Foundations: Computational Physics

The availability of cost-effective teraflops-scale computing capability, coupled with simultaneous progress in nuclear theory and the availability of high-quality precision data from new and upgraded accelerator facilities, offers the prospect of major steps forward in addressing many forefront questions in nuclear physics and nuclear astrophysics. In the foreseeable future, for example, the availability of teraflops-scale computing resources will afford unprecedented progress in understanding the confinement of quarks and the structure of hadrons using lattice QCD calculations, in solving the quantum many-body problem key to making fundamental progress in nuclear structure studies and nuclear astrophysics, and in modeling supernovae explosions in order to understand the origin and abundance of elements in the universe. We therefore expect that world-class, dedicated computational facilities will be crucial to realize the full scientific benefit of the major investments made in CEBAF and RHIC, and to lay the groundwork for future breakthroughs in nuclear structure research and nuclear astrophysics to be afforded by RIA.

An illustrative example is the modeling of supernovae explosions, which also has implications well beyond the near-term goal of understanding the dynamics of supernovae evolution. This problem encompasses nuclear theory, astrophysics, and computer science. It requires modeling (i) the nuclear equation of state up to at least four times normal nuclear density, (ii) the neutrino-nucleus microphysics that is crucial to both the explosion mechanism and associated nucleosynthesis, (iii) the multidimensional neutrino transport in the stellar core, and (iv) the hydrodynamics of convection, rotation, and shock wave propagation.

Similar examples exist in the search for a computational solution to the quantum many-body problem and in seeking an understanding of the confinement of quarks and the structure of hadrons using lattice QCD calculations. In the former case, new world-class computational capabilities will significantly increase the range of exact ab initio calculations of nuclear structure, currently limited to nuclei with $A \leq 10$. New codes and enhancements of existing codes are being developed to simulate the structure of heavy nuclei and dense nuclear matter. These new computational techniques should, in many cases, be applicable to computational materials sciences, atomic physics, and computational chemistry problems. In the case of lattice QCD, calculations using multi-teraflops resources will significantly advance the study of nonperturbative QCD, surmounting many obstacles that limit the current theory. This work will have a profound impact on our understanding of results from CEBAF and RHIC. In addition, the resulting detailed exposition of the structure and substructure of nucleons will be relevant to the particle physics, nuclear science, and astrophysics communities.

International Collaborations and Cooperation

A Worldwide Effort

Interactions with the international community have become key to maintaining the vitality of the U.S. program in nuclear physics. Major experiments around the world invariably involve collaborations of U.S. scientists with their foreign colleagues, and all the major nuclear science accelerator facilities in the U.S. have international user communities. The newest U.S. facilities, RHIC and CEBAF, attract outstanding foreign scientists, who contribute ideas, expertise, and other critical resources for mounting forefront experiments. Foreign participation is substantial. About 40% of the scientists working at RHIC and about 30% of those at CEBAF are from outside the U.S. Even the smaller, lower-energy facilities, both at national laboratories (Argonne's ATLAS, Oak Ridge's HRIBF, and Berkeley Lab's 88-Inch Cyclotron) and at universities (the MIT-Bates electron accelerator, NSCL at Michigan State, and accelerators at Texas A&M, TUNL, the University of Washington, and Yale) likewise enjoy international participation. About 30% of the users of these facilities are foreign. Furthermore, it is not just the contribution of scientists that has been beneficial to the U.S., as substantial contributions of equipment from abroad have greatly enhanced the capabilities of U.S. facilities. For example, at RHIC over $40 million worth of equipment and in-kind contributions has come from foreign sources. In addition, the RIKEN Institute in Japan has set up a center at Brookhaven that helps support both young theorists and young experimentalists who are working at RHIC.

As these examples illustrate, the U.S. does not dominate the international nuclear physics effort. U.S. nuclear scientists account for about 25% of the world's activity. About 50% of the worldwide effort is conducted by CERN member states, and the remaining 25% of the nuclear science community is divided among many other countries, led by Japan and Canada. The number of Ph.D. degrees granted in nuclear physics in the U.S. generally tracks scientific activity. The average has been about 100 per year over the last five years, about a quarter of the world's production.

As research in nuclear physics is truly an international endeavor, access to unique foreign facilities by U.S. scientists is essential for maintaining the excellence of the U.S. program. Experiments at CERN in relativistic heavy-ion physics and at DESY in electron nuclear physics have involved U.S. scientists as major partners, and U.S. researchers have also utilized a variety of other specialized foreign facilities. High-profile experiments in neutrino science, such as SNO, SuperKamiokande, KamLAND, and Borexino, involve substantial numbers of U.S. participants who work at the experimental sites in Canada, Japan, and Italy. Figure 4.8 shows the facilities around the world where the U.S. is represented by a significant community of nuclear scientists.

Shared Facilities, Shared Planning

Major new initiatives for nuclear science are developing in Europe and Japan that will have significant impact on the U.S. planning process—and vice versa. The Japanese Hadron Facility, for example, a high-intensity, 50-GeV proton synchrotron, is under construction and will be the world's premier multipurpose hadron physics facility within the decade. The project is an ambitious undertaking, with programs in hadron, neutron, and neutrino physics. Also under way is another Japanese project at RIKEN that will provide exotic nuclear species via heavy-ion fragmentation. At CERN a major new accelerator, the LHC, is under construction; when complete it will allow the highest-energy heavy-ion collisions to be observed, albeit with a limited running schedule. There is also a proposal for a major new multifunctional accelerator complex at GSI that, if approved and constructed, would attract U.S. researchers. And finally, a variety of high-energy, high-intensity lepton facilities have been proposed in Europe. Collaborating in research at facilities such as these is a cost-effective mechanism for maintaining the breadth of the U.S. program.

Cooperation works both ways. The scientific program of the future RIA facility is certain to see substantial international involvement. And as a prelude to the much more versatile RIA, U.S.-initiated experiments are being mounted at the newest radioactive-beam facilities: ISAC in Canada and RIKEN in Japan. Recommendation 3 of this Plan

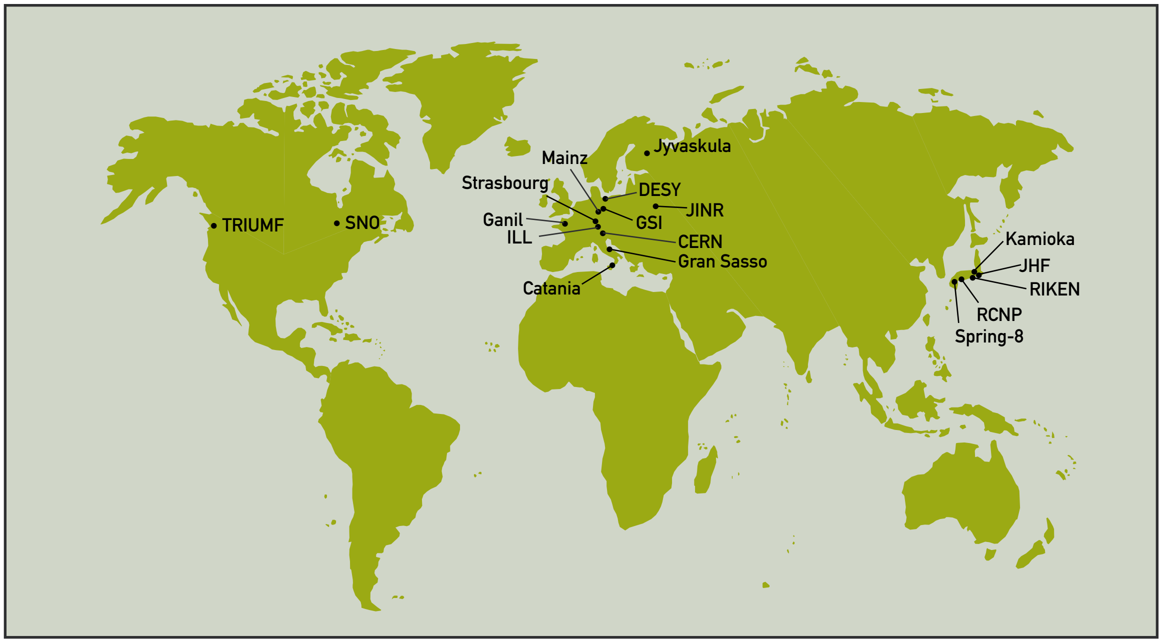


Figure 4.8. Interests abroad. The map shows institutions and facilities in Canada, Europe, and Asia where U.S. nuclear scientists play significant collaborative roles.

speaks to the question of a dedicated underground laboratory within the U.S., which would become the deepest available site to mount experiments requiring extremely low backgrounds and shielding from cosmic radiation. It would also provide a vital center for underground physics within the U.S., as well as a significant enhancement of worldwide capabilities in this area. A U.S. underground laboratory would establish the U.S. as a full partner with the other leading nations, Italy and Japan, who now operate dedicated laboratories for this new frontier of nuclear science.

It is part of the current culture that the international nuclear physics community participates in planning each new major nuclear science accelerator facility, regardless of its location, and this is happening in the U.S., as well as abroad. International observers from the scientific communities in Europe (NuPECC, the Nuclear Physics European Collaboration Committee, a 14-nation organization), Japan (KAKUDAN, the Steering Committee of the Japanese Society of Nuclear Physics), and Canada joined their U.S. colleagues at the 1996 U.S. Nuclear Physics Long Range Planning meeting for the first time. Representatives from these communities also attended the 2001 Long Range Plan Working Group meeting (the Canadian representative was from NSERC, the Natural Sciences and Engineering Research Council of Canada). The 2001 planning process benefited significantly from the input of our foreign colleagues.

The act of terrorism on September 11, 2001, affected nearly every aspect of our national life, including science. The present climate will clearly impact how nuclear science is carried out internationally. Increased security concerns require compliance with more elaborate restrictions imposed by government agencies responsible for homeland security. But it is also essential to U.S. interests that we remain active participants within the international community. For example, about one-half of the physics graduate students in the U.S. are foreign nationals. If history is any guide, many of these students will pursue successful careers in the U.S., where the demand for trained scientists is increasing. We cannot lose sight of the enormous contributions foreign students have made to the U.S. over many years.

International cooperation has proven essential for making many of the major discoveries in modern science. International collaborations focus the world's scientific power on critical questions, often leading to major advances that are beyond the reach of a single country. At the same time, we must maintain the appropriate balance between experiments pursued in the U.S. and in other countries. To remain at the forefront of nuclear science and to preserve our capabilities, we must have local facilities and in-house technical expertise and, at the same time, must provide opportunities for U.S. scientists to exploit the most appropriate facilities worldwide.

Impact and Applications

The special properties of the nucleus and the unique technologies developed to pursue nuclear research continue to lead naturally to an impressive array of applications useful to society's needs. Areas of significant impact include medical diagnostics and treatment, national security, energy production, analytical techniques, environmental science, space exploration, and materials analysis and modification. In addition, nuclear scientists provide the U.S. with an important pool of talented personnel, as underscored in the section, "Education and Outreach."

Technologies emerging from nuclear research play a central role in the arena of human health, and the field of nuclear medicine is a direct descendant of developments in nuclear science. Three areas of particular significance are radioisotopes, diagnostic imaging, and cancer radiation therapy. Nuclear imaging techniques and cancer therapy with protons, neutrons, and heavier nuclei are becoming increasingly widespread and show great promise for improved selectivity and effectiveness.

Nuclear techniques are also essential in providing for the safety and security of our citizenry, and many nuclear scientists are active in this area. For example, airline passenger security is enhanced by the use of neutron activation spectrometers that can detect the presence of explosives in luggage. On a more global scale, our national security demands control over the distribution of enriched uranium and plutonium from dismantled nuclear weapons and the stewardship of the remaining nuclear stockpile—both dependent on the technologies of nuclear science.

Nuclear energy is an important component of the nation's national energy policy. In this area, advanced nuclear fuel cycles and next-generation technologies offer great promise in resolving societal questions regarding safety through increased proliferation resistance and reduced waste streams.

Environmental scientists exploit the exceptional sensitivity of nuclear analytical techniques to obtain information on groundwater resources and their recharge rates, the origin of atmospheric pollutants, oceanic circulation patterns, the rate of carbon dioxide exchange between the atmosphere and the land and oceans, and the historical climate record. This data-gathering is made possible both by observing the decay of radioactive species and by directly counting specific isotopes using accelerator mass spectrometry and atom-trap trace analysis. Such information is often not available by other means. Similar techniques have had great impact in many other fields, including archaeology, artifact dating, art authentication, and the exploration of Mars.

The use of implanted radioactive tracers has long been a powerful tool for materials science and surface studies. In addition to its importance in wear and corrosion studies, radioactive-beam implantation is routinely used in studies of semiconductors, high-temperature superconductors, and the magnetic properties of materials.

Beams of high-energy particles and gamma rays have many applications in industry, from the sterilization of foodstuffs to the curing of epoxies. Industry uses nuclear techniques and accelerators to determine the composition and properties of materials, their structural integrity after manufacture, and their wear in use. Modification of materials through accelerator ion implantation is also widespread, as in the doping of microelectronic circuits, the hardening of prosthetic devices, and the introduction of defects to increase the current-carrying properties of high-temperature superconductors.

The list on the following page highlights some of the areas where the impact of nuclear science is important.

Many of these applications were discussed in considerable detail in the 1996 long-range plan and in the report, *Nuclear Physics: The Core of Matter, the Fuel of Stars,* prepared by the Committee on Nuclear Physics of the National Research Council. Here we discuss recent developments in a few of these areas in greater detail. In the future, we expect significant new applications to be realized, as this Plan is implemented. This section includes a discussion of two proposed facilities—RIA and NUSL—that will have a pronounced impact on new applications.

Areas of Nuclear Science Applications

MEDICAL DIAGNOSTICS AND THERAPY
Radioisotopes
Computerized tomography
Positron emission tomography
MRI with polarized noble gases
Photon therapy
Particle-beam therapy

SAFETY AND NATIONAL SECURITY
Airport safety
Large-scale x-ray and neutron scanners
Arms control and nonproliferation
Stockpile stewardship
Mine detection
Tritium production
Space-radiation health effects
Food sterilization

ENERGY PRODUCTION AND EXPLORATION
Nuclear reactors
Energy-amplifying accelerators
Oil-well logging

ART AND ARCHAEOLOGY
Authentication
Nuclear dating

ANALYTICAL TECHNIQUES
Activation analysis
Accelerator mass spectrometry
Atom-trap trace analysis
Forensic dosimetry
Proton-induced x-ray emission
Rutherford backscattering
Ion-induced secondary-ion emission
Muon spin rotation

ENVIRONMENTAL APPLICATIONS
Climate-change monitoring
Pollution control
Groundwater monitoring
Ocean-current monitoring
Radioactive-waste burning

MATERIALS TESTING AND MODIFICATION
Trace-isotope analysis
Ion implantation
Surface modifications
Flux-pinning in high-T_c superconductors
Free electron lasers
Cold and ultracold neutrons
Single-event effects
Micropore filters

Medical Diagnostics and Therapy

The most important emerging application of nuclear science is in nuclear medicine. *Nuclear Physics: The Core of Matter, the Fuel of Stars* notes:

> In the United States, 1,600 radiation oncology departments operate 2,100 linear accelerators. Nuclear diagnostic medicine generates approximately $10 billion in business annually, radiation therapy using linear electron accelerators about the same, and instrumentation about $3 billion. Over 10 million diagnostic medical procedures and 100 million laboratory tests using radioisotopes are performed annually in the United States. Three areas of particular medical significance are cancer radiation therapy, diagnostic imaging, and trace-isotope analysis.

Radiation therapy. Cancer accounts for approximately 25% of all deaths in the U.S., and a million patients develop serious forms of cancer every year. Approximately half of these patients are treated with some form of radiation therapy. Photon therapy, often complemented by direct irradiation with electron beams, remains the most common form of radiation treatment. However, this type of treatment has the drawback that healthy tissue between the surface of the body and the tumor can receive significant doses of radiation. In order to reduce this side effect, new facilities that center on treatment with particle beams—neutrons, protons, and heavy ions—have opened in recent years. Notable examples in the U.S. are the proton facilities at the Loma Linda University Medical Center in California, the Northeast Proton Therapy Center at Massachusetts General Hospital, and the new Midwest Proton

Radiation Institute at Indiana University, and the neutron facilities at the University of Washington and at Detroit's Harper Hospital. The last of these employs a superconducting cyclotron designed and constructed by staff at Michigan State's NSCL. This superconducting cyclotron technology is now being utilized in a new design for a cost-effective, compact cyclotron to be used for proton radiation therapy of cancer patients.

The accelerators at these facilities are optimally tailored to meet the needs of the medical community. In such facilities, teams of radiologists, physicists, and computer programmers work together to optimize and fine-tune three-dimensional treatment plans (conformal therapy) that maximize dose-deposition in the tumor while minimizing exposure of healthy tissue. The software packages used for these purposes are often derived from simulation programs written for basic nuclear and particle physics research. New cancer treatment protocols are emerging that already show highly promising results for tumors that are otherwise difficult to treat. Particular success has been achieved in the treatment of eye melanomas, and a number of facilities around the world are now dedicated to eye treatment.

Trace isotope analysis and diagnostic imaging. Of the analytical applications of nuclear science, the most important is the use of radiotracers, which find their greatest utility in biology and medicine. Uses range from imaging, to radioimmunoassay (more than 10 million such procedures are carried out each year in the U.S.), to DNA analyses. More than one-third of all patients admitted to hospitals are diagnosed or treated using procedures that employ radioisotopes. These isotopes have chemical properties identical to their stable counterparts, but they decay, with known half-lives, by emitting readily detected characteristic radiation. These molecules thus become tiny transmitters with completely natural biochemical properties. Radioisotopes help researchers to develop diagnostic procedures and to create new treatments for diseases including cancer, AIDS, and Alzheimer's disease. Recent developments in the pharmaceutical industry include the synthesis of "silver bullets," molecules capable of finding and attaching themselves to specific organs or tissue types in the body. Loaded with appropriate radioisotopes, these molecules are of particular interest in the diagnosis and treatment of cancer that has metastasized and is found at many locations in the body, making standard radiotherapy or chemotherapy impractical.

The most important application of radiotracers, constituting more than 90% of medical isotope diagnostic procedures, involves the use of ^{99m}Tc or one of the iodine isotopes. Technetium-99m has a half-life of only six hours, and many of the other isotopes in common use also have relatively short half-lives. The generation and handling of these radioisotopes typically require personnel who have been trained in nuclear science.

Positron emission tomography. The use of positron emission tomography (PET) imaging has grown dramatically over the past decade. It is now a major diagnostic modality. The wide availability of PET in the U.S. has been made possible by advances in detector technology, as well as the distribution of the primary tracer fluorodeoxyglucose (FDG), labeled with ^{18}F. In the field, PET cameras routinely achieve spatial resolutions of 4 mm, and experimental research cameras have achieved 2-mm resolution.

While the clinical importance of PET in cancer diagnosis continues to grow, research on neurological and psychiatric diseases is still a major focus for academic PET centers around the world. These centers have developed dozens of PET tracers to better understand the in vivo biochemistry of disorders such as Parkinson's disease, schizophrenia, Alzheimer's disease (Figure 4.9), mood disorders, and addiction to chemical substances.

In the wake of improved detector technology and improvements in spatial resolution, the development of small-animal PET scanners has become an area of lively research interest. With such devices, researchers can now make use of the results from genomics research to correlate

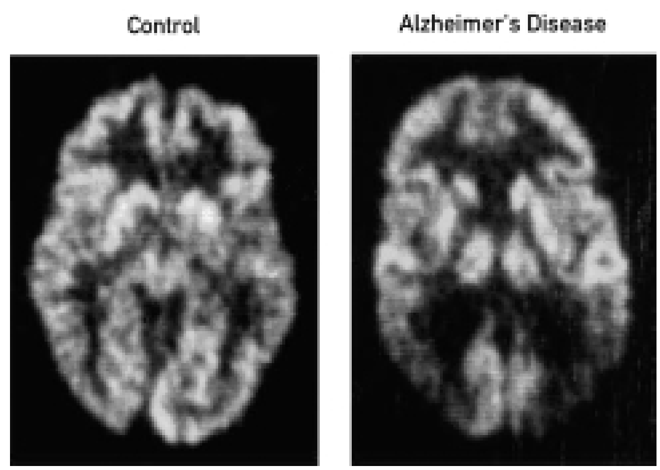


Figure 4.9. Slices of life. Positron emission tomography provides functional and metabolic insights unavailable with most imaging techniques. Here, using ^{18}F-labeled fluorodeoxyglucose as a tracer of brain function, PET highlights the differences between a normal brain and a brain affected by Alzheimer's disease.

genetic alterations with functional changes in rodents. Drug companies now recognize the power of this in vivo functional imaging approach and have begun to incorporate PET into all phases of drug development.

The future will see continued improvements in both detector design and radioisotope production techniques. However, the major advances will result from the design of unique new radiotracers to probe the biochemistry of life. Much of the needed R&D can be done at RIA.

Polarized-gas MRI. At the time of the 1996 long-range plan, researchers had recently demonstrated the feasibility of a new technique for magnetic resonance imaging (MRI) using nuclear-polarized noble gases such as ^{3}He and ^{129}Xe. Images of the gas space of the lungs of small animals, produced using MRI scanners tuned to the rotation frequency of the introduced noble gases, were of unprecedented resolution. Since that time, MRI research using laser-polarized noble gases has grown into a substantial field, involving hundreds of workers, including many physicians. The remarkable improvement in resolution that can be achieved is illustrated in Figure 4.10.

This technique is currently being explored as a diagnostic tool for diseases ranging from asthma and emphysema to pulmonary emboli. Food and Drug Administration trials are currently in progress, and this new imaging technique should become widely available within a few years. Research on this technique has been pursued at universities and has taken advantage of extensive work on polarized nuclear targets carried out at universities and national laboratories.

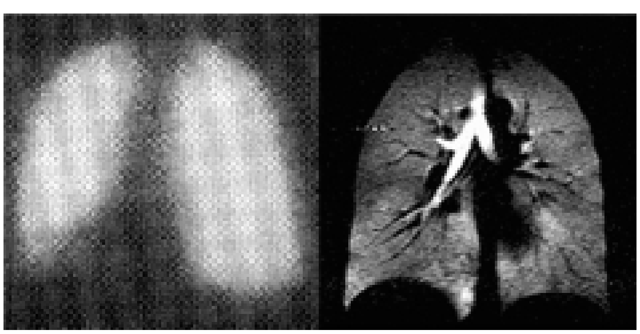


Figure 4.10. Details revealed. Magnetic resonance imaging using polarized noble gases offers dramatic improvements in resolution over current techniques. On the left is a picture taken with the method in current use, in which the patient inhales a radioactive isotope, and a gamma camera is used to image the lung. The resolution is limited to 1–2 cm. On the right is an image taken with the noble gas–imaging technique.

National Security

With the end of nuclear testing, the U.S. is relying on the Science-Based Stockpile Stewardship (SBSS) program to ensure the reliability and performance of the aging U.S. nuclear weapons stockpile. Achieving this goal involves (i) obtaining a better understanding of the nuclear weapons tests that were carried out in the past and (ii) creating new tools to understand the performance of nuclear weapons. Nuclear scientists continue to play important roles in this program, not only in carrying out research required to ensure our continued national security, but also in occupying management and advisory positions. For example, two of the national defense laboratories (Sandia and Los Alamos) are currently led by nuclear scientists.

Archival nuclear weapons data. It is crucially important to fully understand the archival data that was accumulated during the nuclear testing period, as these are the only data we have that accurately reflect the conditions reached during a nuclear explosion. Understanding these historical data requires reanalysis using modern tools and improved input data from nuclear cross-section measurements. Device performance is measured by post-test counting of the radioactive isotopes produced by charged-particle- and neutron-induced reactions on foils of various elements inserted into the device. However, quantitative interpretation of archival radiochemical data is seriously hampered by a lack of measured cross sections for radioactive nuclei that are both produced and burned in a nuclear test. Building on recent progress in nuclear science, we have begun to address this deficiency. Advances in nuclear theory now provide the means to calculate the reaction rates of the radioisotopes of interest with improved accuracy. Similarly, the state of the art in experimental measurements has also progressed. An advanced detector array (GEANIE) constructed for nuclear physics research and the high-intensity neutron beams at LANSCE (a facility built for nuclear physics) recently made possible the first measurement of the ^{239}Pu(n,2n) reaction—a measurement that had been impossible with earlier technology. The resulting data are very important in understanding the yield of a nuclear weapon, and the achievement was recognized by a National Nuclear Security Administration Defense Programs Award of Excellence.

Diagnostic tools. The development of new diagnostic tools provides vitally important new capabilities to the stockpile stewardship program. In particular, radiography has become perhaps the most important diagnostic tool available to assess the performance, safety, and reliability of the nuclear weapons stockpile. Traditionally, x-ray radiography has been used for hydrodynamic tests of weapons primaries, but it suffers from severe attenuation and scatter problems when used on radiographically thick objects. Proton radiography is acknowledged as a superior probe for hydrotests. It provides a highly penetrating probe and is able to provide a multipulse 3-D "motion picture" of the imploding primary, with high resolution and minimal backgrounds. This technological breakthrough relied on many of the tools and skills used in nuclear physics and was, in fact, invented by personnel coming from the LAMPF nuclear physics program. Proton radiography is already being used to provide data for the SBSS program and is a prime candidate for a future hydrodynamics test facility, crucial to SBSS. Another application to the SBSS program derived from the nuclear physics program is neutron resonance spectroscopy, used to measure temperatures and velocities inside high explosives. It is based on techniques developed for the parity-violation experiments using epithermal neutrons at Los Alamos.

Nuclear Energy

Nuclear science remains important in energy production, and nuclear scientists constitute an important fraction of the personnel who supply the U.S. with its energy. Fission reactors currently produce about 19% of U.S. electricity (17% worldwide), and the total amount of electricity generated by nuclear power in the U.S. is the largest of any nation (>650 GW). Nuclear energy provides a viable option for reducing the use of hydrocarbon fuels and, hence, the emission of carbon dioxide into the atmosphere. However, public concerns regarding the potential hazards of nuclear proliferation and high-level radioactive waste have limited the use of nuclear energy in the U.S.

Major new national initiatives have been launched to address these concerns:

- New technologies offer the promise of inherently safer reactor designs.
- Advanced fuel cycles and fuel-conditioning methods can reduce the nuclear waste stream and enhance proliferation resistance.
- Researchers in the U.S. and in Europe are studying accelerator burning of actinide waste and surplus plutonium in subcritical assemblies.

In the accelerator transmutation of waste (ATW) approach, very high-intensity accelerators would be used to transmute long-lived radioactive species into shorter-lived species or even stable isotopes. We may thus be able to minimize the politically and socially complex problem of long-term radioactive waste storage, since the end products would decay into stable nuclides within decades rather than millennia. This would reduce the duration of required sequestration and permit use of a much wider variety of proven and credible confinement technologies.

In addition to serving in the disposal of radioactive wastes, and in the production of the tritium required to maintain the required stockpile of nuclear weapons, intense beams from future accelerators may also be used for energy production in subcritical, accelerator-driven reactors. Such devices would operate with subcritical amounts of fissionable material, since the beam from the driver accelerator would produce the necessary neutrons from a spallation source, without need for a self-sustaining chain reaction. Serious accidents due to runaway reactions would then be impossible. When the accelerator is turned off, energy (and thus heat) production by fission would stop virtually instantaneously. Since such facilities would largely burn their own waste into short-lived radioactive remnants, they could be operated at a much-reduced environmental cost. Moreover, they could utilize the thorium-uranium cycle, which does not require reprocessing of fuel elements, with its associated risk of weapons-grade material being diverted. This would greatly reduce the risk of nuclear weapons proliferation.

Materials Analysis

Nuclear physics has provided an array of analytical techniques that are employed in archaeology, art, materials science, chemistry, biology, and space exploration. A well-known example, accelerator mass spectroscopy, is now used routinely at many dedicated facilities around the world. It has recently been applied to study the flow of ocean currents and global climate change. Other analytical tools that have been developed by nuclear scientists are now being applied to problems in the electronics industry and to address issues of radiation damage.

Single-event effects. The performance of microelectronic devices can be seriously impaired by ionizing radiation. A charged particle intruding near a P-N junction may cause a "single-event effect" (SEE) by generating excess electrons and holes, which are then separated by the electric field of the junction and swept to a nearby device contact. If the collected charge exceeds a critical threshold value, the memory state of the device is changed unintentionally. Malfunctions due to SEEs become an increasing concern as the packing density of computer chips grows. Understanding SEEs is essential for the design of microcomputer chips, especially in spaceflight or in high-altitude military applications. Accordingly, all microcircuits designed for space applications must pass "radiation-hardness" tests that are currently performed with beams of neutrons and charged particles provided by research accelerators. Government and industrial users are actively studying SEEs using accelerators at Berkeley Lab, Brookhaven, Los Alamos, Michigan State, and Texas A&M. As a result of the experience gained from accelerator-based testing of SEE-related failures, the reliability of circuits against SEE failure has been improved more than tenfold. For example, it is possible to produce neutron beams that very closely mimic the energy distribution of high-energy neutrons (which in turn produce charged recoil particles) observed at 30,000 feet, but with an intensity that is more than a thousandfold higher. The flight certification of the Boeing 777 (the first all "fly-by-wire" aircraft) relied in part on measurements made at Los Alamos of the SEE-resistance of the aircraft electronics.

Radiation damage studies. A number of applications require high resistance to radiation damage, a topic in which nuclear science plays a significant role. As an example, accelerator-driven neutron sources are finding a wide range of applications, from ATW and energy production (as discussed earlier) to materials science, which uses neutron scattering as an analytical tool. In all of these high-intensity applications, radiation damage in the source and in nearby equipment is a serious concern. For instance, the SNS is currently carrying out studies to address issues of reliability in high-power (1–2 MW) mercury spallation targets. In a series of recent measurements at LANSCE, a new form of radiation damage was discovered: pitting of the walls (leading to eventual wall failure) enclosing the mercury target. This type of damage, in which the high energy density deposited from a charged-particle beam causes the formation of cavitation bubbles in the mercury, had never been observed before.

Developing Capabilities

The development of new tools and facilities to address major questions in nuclear physics has always been an essential component of the national program. At the same time, nuclear scientists take advantage of these advances in fundamental science to address pressing issues pertinent to the health, security, and economic vitality of the nation. Here we offer an overview of two emerging capabilities that have immediate significant applications and two large facilities proposed in this Plan that will provide important new capabilities in the future. All of the applications discussed are being developed by nuclear science.

Free electron lasers. The invention of the laser as an intense source of monochromatic and coherent light has had a profound impact on many areas of science and technology. Many new applications are, however, hampered by the inability of conventional lasers to produce monochromatic light over a broad range of wavelengths, from the infrared through the visible to the ultraviolet, or to produce and sustain extraordinarily high power levels. Free electron lasers (FELs) can overcome these limitations. Recently, a highly focused and powerful experimental free electron laser, constructed at Jefferson Lab, has become the world's most powerful tunable laser (see Figure 4.11). The pioneering energy recovery system developed at this FEL is another example of advanced accelerator research that promises to have widespread applicability in basic research and in industrial applications.

Worldwide industrial interest in the potential applications of FELs is growing. Intense light at the appropriate wavelength has a demonstrated ability to alter the chemistry, topography, and morphology of materials, surfaces, and interfaces. For example, one can modify the surface of polymer films, fibers, or composites to improve adhesion, to enhance dye uptake, or to enhance effectiveness in filtration uses. FELs could be used for surface treatments by companies that forge, coat, treat, and clean metals of all kinds and by businesses that micromachine materials and parts, as well as by semiconductor manufacturers. FEL proof-of-concept experiments have included investigations of assisted chemical-vapor deposition, a technique used to produce high-quality coatings and thin films for electronics and microcomponents. FELs have also been studied for use in processing nylon, polyester, and polyimides. Using FEL techniques, manufacturing industries could do away with many environmentally hazardous wet-chemical surface treatments now employed.

Atom-trap trace analysis. A striking example of the synergy between basic and applied research has been the development by nuclear scientists of atom-trap trace analysis (ATTA) as a tabletop system for the detection of noble gas isotopes. Krypton-81, with a 200,000-year half-life can now be detected at the parts-per-trillion level and used to understand the flow of groundwater and to date polar ice. Furthermore, applying this technique to the fission fragment ^{85}Kr offers new possibilities in nonproliferation studies and in the detection of cladding failure in nuclear reactor fuel rods. New ATTA research in the trace analysis of ^{41}Ca has the potential for advancing studies of bone metabolism and for applications in archaeology. These applications arose directly from concerted basic research efforts to develop atom-trap technology to study physics beyond the Standard Model.

National Underground Science Laboratory. A host of national security issues, ranging from nonproliferation to counterterrorism, depend on the ability to measure trace quantities of radioactivity. The development and operation of ultrasensitive counters is often best done in deep underground locations, where counting can be done free of backgrounds generated by cosmic-ray muons. Much of the technology for such counting has grown out of underground science, particularly the efforts of neutrino physicists to measure radioactivities at the level of a few atoms in solar neutrino and double-beta-decay experiments. The underground laboratories built to house such experiments are also ideal sites for counters important to national security.

For example, one of the tools used by the U.S. to monitor underground nuclear testing involves the detection of telltale radioactive gases, such as the noble gas xenon. A security concern is the possibility that some rogue nation could secretly develop nuclear weapons by testing deep underground, in cavities designed to minimize the seismological signals of the explosion. Such efforts to muffle explosions, however, greatly increase the emission of radioactive gases. In particular, a large fraction of the energy is converted into radioactive xenon, which diffuses to the surface and is carried off into the air. Thus the U.S. Air Force carries out airborne sampling for such radioactivities to guard against clandestine activities. The samples collected are counted in facilities deep underground, using counters that are a product of basic neutrino research. The first such detectors were developed to measure few-atom quantities of the radioactive noble gas ^{37}Ar produced in the historic chlorine solar neutrino experiment.

One of the initial goals of the NUSL proposal is to provide the first multipurpose ultralow-level counting facility—a facility that will allow us to advance many new detector technologies. NUSL is also expected to house facilities for counting samples of importance to national defense and industry. (The Air Force program, now based in Europe, would like to relocate to NUSL.) There are several other important security issues—including the use of

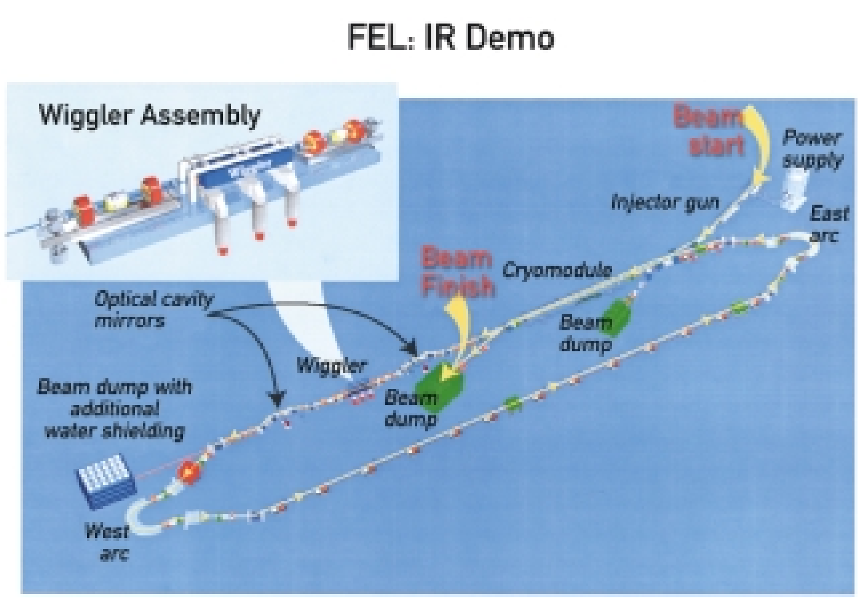


Figure 4.11. A world-record tunable laser. Free electron lasers work by coaxing coherent radiation from electrons by subjecting them to the alternating magnetic fields of a wiggler. As they “wiggle,” the electrons emit light, whose wavelength can be tuned by varying the wiggler gap through which they pass. This schematic shows the Jefferson Lab FEL, which has achieved world-record intensities for a tunable laser.

advanced sensors to detect activities in deep underground bunkers—that various national laboratory scientists have addressed in connection with NUSL.

Rare Isotope Accelerator. In addition to the applications outlined in more detail below, we expect RIA to be applied to studies of space radiation effects using stable and radioactive beams, measurements of neutron cross sections, studies of neutron damage, and radiation-effect studies using high-energy neutrons produced by projectile fragmentation.

National health—Medical applications of radioisotopes are restricted to the narrow range of manufactured isotopes currently available. RIA will provide a unique resource for exploring the vast territory of uncharacterized nuclei whose lifetimes and radioactive emissions may be appropriate in nuclear medicine. RIA's very high beam intensity, coupled with its mass- and fragment-separation capabilities, will provide opportunities to generate a wide variety of high-purity isotopes that are not currently available. With a wider variety of isotopes identified, it should be possible to develop reliable supplies of materials best suited for diagnostic and therapeutic procedures.

RIA will have the ability to postaccelerate radioactive species and to implant them into various substrates. This will provide a new diagnostic tool to assess the wear of artificial joints and thus to advance means of producing more wear-resistant devices. This will provide a very tangible benefit to the health of Americans: Approximately half of all artificial joint implants are replacements of worn implants. Thus, improved wear resistance can result in a significant reduction in trauma to patients, as well as a substantial cost savings (joint replacement is a $1 billion per year enterprise).

National security—RIA will provide significant new capabilities for the SBSS program. To arrive at a quantitative understanding of nuclear weapons performance, additional information is needed for reactions involving radioactive nuclei and isomeric nuclear states. RIA will provide the capability to measure a number of important reaction cross sections, allowing us to improve the theoretical models used to calculate all of the nuclear reactions that occur during a nuclear explosion.

Nuclear energy—The nuclear cross sections for burning nuclear waste in the fast-neutron flux characteristic of ATW are poorly known. RIA could be used to produce selected radioactive targets for the measurement of the important fission and capture cross sections at a neutron facility. The measurements made possible by RIA would be extremely valuable in improving the theoretical models used in ATW calculations. Even more important, RIA will provide a means to determine the most effective process to burn nuclear waste by simulating the environment in which the waste would be burned.

Radioactive-beam implantation—With RIA's high intensities and the wide range of isotopes it will produce, materials modification studies using doping and annealing techniques could be greatly extended, providing new methods for improving the properties of materials.

Technology Transfer

While the emphasis of this discussion has been on the direct application of specific nuclear techniques, it is important to note tangential benefits, as well. Fundamental research in nuclear physics drives many new developments in instrumentation and electronics, which, while not nuclear applications per se, find widespread application in many important areas. For example, rapid switching circuits recently developed for the high-power microwave transmitters that drive the linear electron accelerator at MIT-Bates are now being adapted for application in state-of-the-art radar systems used by the U.S. military. They will replace vacuum-tube modulators in the transmitters for two important U.S. Navy shipboard radar systems.

As basic nuclear science pushes to explore new frontiers, new and promising applications of nuclear technology can be expected to emerge and to have a continued important impact on our nation's economy and in areas such as health and national security. Nuclear science's vibrant and intellectually stimulating research environment encourages innovative and unconventional approaches to problems. Its broad technical infrastructure makes possible swift tests and verifications of new ideas or emerging cross-links among disciplines. Maintaining a world-leading role in nuclear science is a key to realizing the full benefits of this potential.

5. Looking to the Future

Earlier chapters of this Plan have laid out the extraordinary scientific opportunities that lie before us in the coming decade and have described the facilities we have at hand to address them. Setting priorities to address these opportunities involves consideration of a number of factors, the most important of which are effective utilization of existing facilities, investment in the future, and balance across the program.

Many of the opportunities we foresee are unique and exist only because of considerable investments that have been made in new accelerators and detectors. Effective utilization of these facilities will allow our community to make substantial advances in our understanding of nuclear physics and to provide the nation with the largest return on its prior investment in the field.

Investment in the future is equally important. Scientific goals change as new results are obtained, and the capabilities of our facilities must evolve to meet these new challenges if we are to ensure the continued vitality of the field.

And finally, balance across the program comes into play because we wish to lay out a coordinated framework that will make progress possible in several subfields of nuclear science. While our community is fortunate to have two major new facilities, it should be remembered that a significant number of the scientific questions we wish to answer will not be addressed at either of them. Substantial progress in other subfields will rely on the funding of new initiatives.

In this chapter, therefore, we address these three factors—each a driving force behind progress in the field—by defining a series of initiatives that, if fully funded, will enable the U.S. to participate in the most important and exciting areas of nuclear science research. Some of these initiatives promote productive operation of existing facilities; others involve new investments. The first four of these initiatives directly address the priority recommendations of the Long-Range Plan Working Group.

Capitalizing on the Nation's Investments

RECOMMENDATION 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 new facilities, RHIC, CEBAF, and*

NSCL—which will greatly enhance the impact of the nation's 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.*

Facility operations: The Facilities Initiative. Consistent federal investments, guided by NSAC long-range plans over the past three decades, have provided the U.S. with the world-leading nuclear science facilities described in Chapter 3. The guidance of the 1989 and 1996 long-range plans led to the successful completion and operation of our newest facilities, CEBAF at Jefferson Lab, RHIC at Brookhaven, and the coupled cyclotron facility at Michigan State's NSCL. With these investments, U.S. scientists are poised to make significant advances in answering many of the important scientific questions discussed in Chapter 2. At the same time, improvements in the existing low-energy accelerator facilities at national laboratories and universities continue to provide new and outstanding research opportunities for the pursuit of compelling scientific questions. The forefront investigations of approximately 3000 research users worldwide are directly tied to the performance of these U.S. national user facilities, and some 500 students and postdoctoral fellows—the next generation of nuclear scientists—rely on these facilities for their training. Unfortunately, fiscal constraints on the nuclear physics budgets have limited the exploitation of these scientific opportunities over the past several years.

Increasingly, facilities are forced to reduce operating hours, curtail new research efforts, and restrict the capabilities that they can offer to the community. Table 5.1 summarizes for each of the U.S. national user facilities the number of scheduled operating weeks for fiscal year 2001, together with the number of weeks the facility could operate with an optimal funding scenario. The table also includes the estimated size of the user community for each class of facility. In the past year, these facilities ran at 15–45% below their optimal levels.

An overall increase of approximately 15% in operating funds would eliminate this shortfall and allow scientific opportunities to be pursued in line with the carefully laid-out long-range plan for nuclear science, thus ensuring the continued vitality of this important field of science. The argument for such an increase is twofold.

Facility	FY01 operations (weeks)	Efficient operations (weeks)	No. of active users
Electron accelerators			1000
CEBAF	33	40	
MIT-Bates	26	35	
Relativistic heavy-ion collider			1000
RHIC	14	30	
Light- and heavy-ion facilities			1000
NSCL	Under Construction	40	
ATLAS	39	43	
88-Inch Cyclotron	35	42	
HRIBF	20	37	
IUCF	26	39	

Table 5.1. Scheduled operating weeks at national user facilities. The second column includes only operations funded directly by agency program funds.

First, the efficiency of each of these accelerators is being strained by the restricted funds available for operations. Every effort has been made to reduce the fixed costs of operations, and the levels of operation indicated in Table 5.1 were only achieved by deferring maintenance—a mortgage against future sustained performance. Accordingly, with constant-dollar funding, the operating hours for some facilities may be reduced by as much as 20% in fiscal year 2002, as necessary operational improvements are made. The experimental programs are similarly constrained by the limited support for installing, maintaining, and upgrading experiments to do the best science. In summary, an increase in operating funds is necessary merely to maintain the current operational schedule, and to promote a level of productivity commensurate with that schedule.

Second, operating hours can be increased to the optimal levels with disproportionately modest increases in funding. The value of doing so is reflected in the high demand for these user facilities—demand that typically exceeds the available operating time by factors of two or more. In addition, these facilities are the primary research tools of many of the nation's university groups. Therefore, their operations are essential to the effective training of the next generation of young scientists. These facilities also provide much of the core of accelerator science expertise that is necessary to design and construct the next generation of scientific tools, both in nuclear science and elsewhere. An excellent example of the latter is the important contributions of scientists from Jefferson Lab and RHIC to the SNS being constructed for the Basic Energy Sciences community.

As a consequence, we strongly recommend a 15% increase in operating funds across the complex of U.S. facilities. This increase will produce a much larger increase in scientific productivity, as a product of increased operating hours, improved reliability as deferred maintenance is performed, and an enhanced ability to upgrade experimental equipment.

University research. Over the past decade, nuclear science in the U.S. has relied on increasingly complex experiments requiring greater resources, in an essentially static funding environment. Facilities have become increasingly centralized, and, because of tight overall budgets, this centralization has been accompanied by a general deterioration in the research infrastructure at universities. While new world-class user facilities, such as RHIC and CEBAF, are the centerpieces of today's nuclear science program, the critical importance of maintaining a healthy equilibrium between the university and national laboratory programs cannot be overstated: The universities continue to play a unique role in carrying out research and in connecting it with the education and training of young people (see Chapter 4, pages 98–106).

University-based research groups continue to be the intellectual driving force in physics, with approximately 70% of all physics publications originating in academic institutions. Universities also provide opportunities for cross-fertilization among disciplines, bringing new ideas into nuclear science and stimulating new research directions. Furthermore, much of the instrumentation employed at the national facilities was designed and constructed at universities. Most importantly, though, strong university research groups and laboratories are vital to attract and train the young scientists needed for the nation's technical work force. University-based laboratories are particularly attractive to students, both undergraduate and graduate, because they provide a unique environment for young people to acquire hands-on training in the campus environment. A student's first taste of research can often develop into a life-long career. Finally, it should be noted that the funds invested in universities are highly leveraged, because at least some of the administrative support and infrastructure are provided by the home institutions.

Approximately one-third of Ph.D.'s trained in nuclear science enter private industry and thus play important roles in the high-technology economy. Nuclear science students acquire not only an ability to think critically, but also highly marketable skills in data analysis, computing, and equipment design and construction. Because of the collaborative nature of nuclear science research at the major laboratories, students also develop strong management and communications skills that prepare them for leadership roles in other sectors of society. Notably, two popular career paths for recent physics Ph.D.'s have led to areas of finance that make use of strong computational skills and to technical or industrial consulting work, where project management experience is indispensable. Strong university research groups provide the environment and training for these skills.

In 2001, for the first time in the past 14 years, the number of physical science Ph.D.'s granted in the U.S. declined. (Students studying nuclear physics account for about 8% of all physics graduate students in Ph.D.-granting departments in the country.) Undergraduate enrollment in science generally, but particularly in physics, is also declining. The eroding university-based infrastructure is making it increasingly difficult to compete for the best students.

A strong nuclear science program is of strategic importance to the U.S. It is essential that the field train the young scientists necessary to maintain world leadership in this important field of science. The significant scientific, financial, and human resource contributions of university programs are a core component of the highest-priority recommendation of this Plan; the current and future vitality of nuclear science depends critically on strengthening university-based laboratories and research groups.

An increase of 15% overall, followed by constant effort in the out-years, is needed to maintain the scientific excellence of university-based research, to continue to identify and educate graduate students to meet the future needs of basic and applied research, and to maintain the high level of university-based nuclear science education and outreach at all levels.

Restoring balance: The Nuclear Theory Initiative. Theoretical research is crucial in providing intellectual direction in nuclear physics. It creates new concepts and new ways of thinking about nuclear physics—and physics in general. It motivates and guides experimental activities, and it synthesizes knowledge gained from experiments into new and more general conceptual frameworks. As discussed in previous sections, nuclear theorists have made vital contributions in each of these areas during the past five years. Although nuclear theory has accomplished much in the past decade, the opportunities will be even greater in the future. Among the questions facing theorists are: What processes operate in the universe—from the Big Bang, to hydrostatic stellar burning, to core-collapse supernovae—to synthesize new nuclei via exotic radioactive isotopes? What are the phases of strongly interacting matter as a function of temperature, density, and isospin? What is the shape of the "new Standard Model" of strong and electroweak interactions, and what might be its signatures in nuclear processes? What is the origin of confinement and chiral symmetry-breaking in the quantum chromodynamics (QCD) vacuum? Why are hadronic structure models based on constituent quarks so successful? And what is the microscopic mechanism of nuclear binding in light and heavy nuclei?

As these questions illustrate, the scope of nuclear physics has grown dramatically during the past ten years. However, the resources allocated for theory have not kept pace, thereby limiting the effort to fully address the new and exciting developments in the field. The latest DOE manpower survey shows that the number of nuclear theorists at national labs has actually decreased since the 1986 census, while the number of experimentalists has increased by 30%; the current ratio of experimentalists to theorists is six. Within the DOE nuclear physics budget, theory has declined from 7.5% of the total at the time of the first long-range plan (which, in 1979, recommended an increase to 10%) to less than 5% now.

A consensus has emerged within our community that this situation must be addressed. At each of the four "town meetings," nuclear experimentalists emphasized the importance of theory in guiding the experimental program and interpreting its findings. It is imperative to significantly increase, relative to the rest of the nuclear physics program, funding for nuclear theory in order to create new theory positions. In implementing this recommendation, we recommend two steps to see that the increased theoretical effort is effectively directed. First, the agencies should appoint a panel of experimentalists, senior theorists, and some of the field's best young theorists whose charge would be to identify how funding increases could be targeted to the areas of greatest promise. This panel could be an NSAC subcommittee. Second, the DOE should immediately establish a new program of "National Nuclear Theory Fellows" to create new nuclear theory postdoctoral and junior faculty bridge positions. Fellowships would be awarded on a competitive, peer-reviewed basis, as in the current DOE Outstanding Junior Investigator program. The goal of this new fellowship program would be to attract and retain young theorists of the highest caliber. In addition to developing the details of this new program, the proposed nuclear theory panel should develop, in consultation with the community, additional mechanisms for implementing increased nuclear theory support.

The establishment of the National Institute for Nuclear Theory, which resulted from a previous long-range plan over a decade ago, has provided nuclear science with an intellectual shot in the arm. The opportunity now exists to provide the field with a similarly effective—and urgently needed—boost through a relatively modest, targeted increase in nuclear theory support.

Maintaining World Leadership: The Rare Isotope Accelerator

RECOMMENDATION 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. RIA is required 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.

The atomic nucleus is a complicated quantum system where three of nature's forces (weak, strong, and electromagnetic) play important roles. One of the major challenges of science is to understand how nuclear structure arises from the various constituent parts of a nucleus and their interactions. However, we lack an important tool needed to answer this challenge, namely, the ability to vary the ratio of the two main components of a nucleus—neutrons and protons—over a wide range, far from the configurations of stable nuclei. Today, this tool is within reach: The technology of high-intensity heavy-ion accelerators and experimental techniques have now advanced to the stage where a next-generation research facility, able to produce and study rare isotopes with a great excess of neutrons or protons, is now feasible. This facility would also allow us to probe the origin of the elements and to produce nuclides previously made only in the most violent explosions in the universe.

In response to these new opportunities, the nuclear science community has proposed the Rare Isotope Accelerator (RIA) project, a bold new initiative in exotic-beam facilities. It combines the advantages of in-flight production and separation of rare isotopes, which is extremely fast, efficient, and chemistry-independent, with the capability of delivering high-quality reaccelerated beams. A schematic layout for RIA is shown in Figure 5.1. The facility will provide beams of rare isotopes with energies from thermal to nearly 400 MeV per nucleon. Fast rare-isotope beams can be used directly in experiments in Area 4, while by coupling to a postaccelerator via in-flight isotope separation and stopping in a buffer gas, or by more traditional isotope separation on-line (ISOL) techniques, experiments in Areas 1 to 3 will be possible with a wide variety of reaccelerated beams.

The scientific justification for RIA has three broad themes:

- Investigations into the nature of nucleonic matter
- A quest to understand the origin of the elements and energy generation in stars
- Tests of symmetries and of fundamental conservation laws

The first of these concerns the structure of atomic nuclei themselves and the interactions within the nuclear medium that determine their existence and properties. RIA will define and map the limits of nuclear existence and allow us to explore the structure of the exotic quantal systems that inhabit these boundaries. The expanded inventory of nuclei made accessible by RIA will allow us to isolate, amplify, or reveal new phenomena, new types of nucleonic aggregations, or key nuclear interactions in ways that beams of stable nuclei cannot do. Moreover, reactions with neutron-rich nuclei will help elucidate the nuclear equation of state (EOS), with astrophysical ramifications for the structure of neutron stars and supernovae.

The second theme addresses questions about our own origins and about the most cataclysmic cosmic events since the Big Bang. RIA will provide key data, such as masses, lifetimes, and reaction rates, needed for a quantitative understanding of important nucleosynthesis processes, especially the r-process.

And finally, the third theme concerns our understanding of the basic laws of nature and the basic interactions among the fundamental constituents of the universe. With RIA it

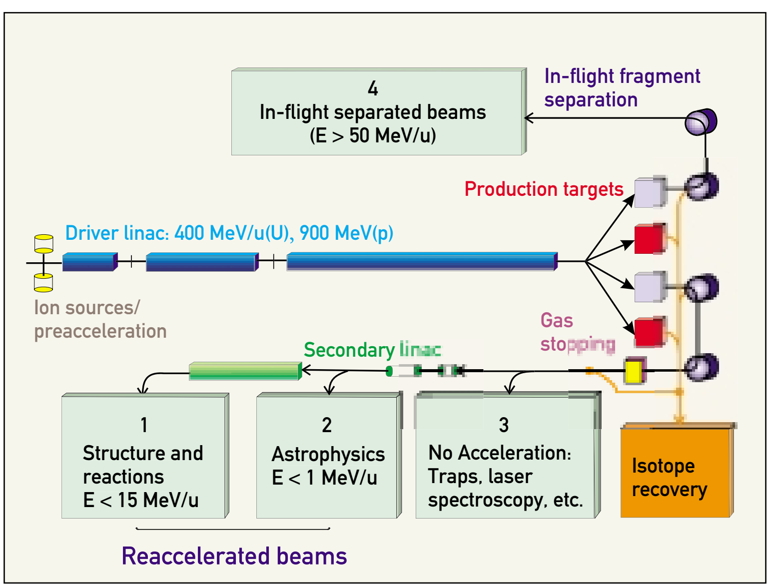


Figure 5.1. Simplified schematic of RIA facility. Rare isotopes at rest in the laboratory will be produced by conventional ISOL target fragmentation, spallation, or fission techniques and, in addition, by projectile fragmentation/fission and stopping in a gas cell. Upon extraction, these stopped isotopes can be used at rest for experiments in Area 3, or they can be accelerated to energies below or near the Coulomb barrier and used in Areas 2 and 1, respectively. The fast beams of rare isotopes, which are produced by projectile fragmentation/fission, can also be used directly after separation in a high-resolution fragment separator (Area 4). Thus, RIA combines the advantages of conventional thick-target ISOL techniques and transmission-target projectile fragmentation/fission techniques.

will be possible to advance the study of time-reversal and parity violation and to carry out new experimental tests of the unitarity of the CKM matrix and of other aspects of the electroweak interaction.

The key to the scientific discovery potential of RIA is its ability to provide the highest-intensity beams of stable heavy ions for the production of rare isotopes. RIA's driver accelerator will be a flexible device capable of providing beams from protons to uranium at energies of at least 400 MeV per nucleon, with beam power in excess of 100 kW. With this flexibility, the production reaction can be chosen to optimize the yield of a desired isotope. In comparison to the two main competing in-flight facilities, the Radioactive Ion Beam Factory at RIKEN and the GSI upgrade, RIA has two advantages. First, RIA's capability for postacceleration (not included in either of the other two projects) will allow a wider range of studies and will include the measurement of nuclear reactions at astrophysical energies and the search for new heavy elements with long lifetimes. Second, the acceleration scheme of RIA's primary-beam linac is planned to be 20-fold more efficient than either of the other facilities and hence able to deliver significantly more primary-beam power. In comparison to the main ISOL competition, ISAC at TRIUMF, RIA has higher primary-beam power and a more flexible combination of ion sources, which will provide higher intensities and a wider variety of rare isotopes.

The extraction of exotic nuclei at RIA will employ three methods. In the first, a thick ISOL-type target will be coupled to an ion source and a postaccelerator for energies beyond the Coulomb barrier. This method will provide the most intense reaccelerated beams of those elements with chemistry favorable for rapid release. A second target area will utilize a thinner target and a recoil mass separator that can operate in two modes. In one mode, the fast mass-separated exotic nuclei will be energy-degraded and then stopped in a gas catcher from which they can be rapidly extracted for reacceleration in the postaccelerator. This will provide intense beams of short-lived isotopes or elements that are difficult to obtain from the standard ISOL target. In the second mode of thin-target operation, after mass separation, the ions from the target can be used directly as fast beams for experiments at high energies. In all cases, stopped nuclei can also be used for decay experiments, they can be injected into atom or ion traps, or they can be accelerated to low energies suitable for astrophysics studies.

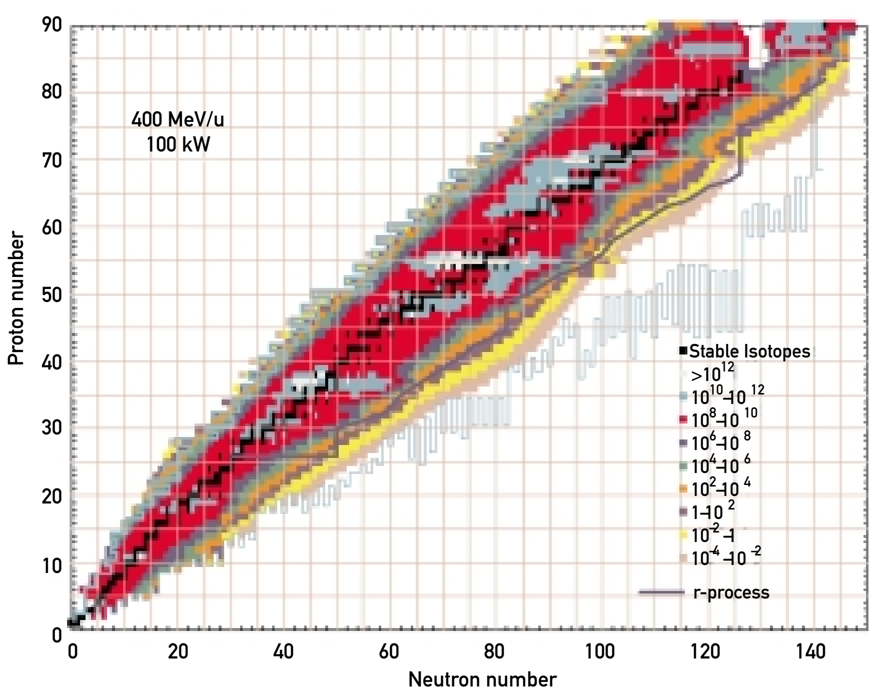


Figure 5.2. Estimated yields for rare isotopes to be available at RIA. The intensities are given in ions per second.

Expected mass-separated intensities from RIA are shown in Figure 5.2. Many of these nuclei have never before been available as in-flight or reaccelerated beams. Generally, the intensity of rare isotopes will be more than two orders of magnitude greater than with any existing or planned facility. As shown in the figure, essentially all the nuclei that participate in the various astrophysical processes, such as the rp- and r-processes, will be available for study. The high intensities of rare isotopes will allow a full exploration of the limits of nuclear stability and will provide a wide range of isotopes for each element.

The National Underground Science Laboratory

RECOMMENDATION 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 will position the U.S. nuclear science community to lead the next generation of solar neutrino and double-beta-decay experiments.

Physics is in the midst of two major intellectual revolutions: The foundation for what will be the new Standard Model is being laid at the same time that some of the deepest secrets of the cosmos are being revealed. A deep underground science laboratory will play a leading role in both of these revolutions, housing next-generation experiments that will not only answer significant nuclear physics questions, but also address key issues in the related fields of particle physics, astrophysics, and cosmology, as well as in earth sciences, materials physics, and geomicrobiology. The National Underground Science Laboratory (NUSL) will also have important applications in industry and in national security.

Remarkable discoveries about the neutrino have been made recently with the large underground Cerenkov detectors at SuperKamiokande in Japan and at SNO in Canada (see pages 77–83). Taken as a whole, the data indicate that neutrinos change their flavor, undoubtedly a result of "oscillations" between neutrino species with mass. This experimental evidence clearly demonstrates that the Standard Model is not complete. But the neutrino remains very mysterious: Oscillations yield mass *differences,* but what are the actual masses of the neutrinos? How do neutrinos mix and why is the mixing so different from quark mixing? The total number of leptons of one flavor in the universe is not fixed, but is the *total* lepton number still conserved? Is the neutrino different from the antineutrino? Are there "sterile" neutrinos—that is, neutrinos that react much more weakly with detectors than the three known neutrino types? Do neutrinos respect the symmetry of time reversal?

Lepton-number violation in the early universe and time-reversal violation both bear on the puzzling question of why the universe appears to contain much more matter than antimatter. The absolute scale of neutrino masses is needed for an understanding of dark matter and the large-scale structure of the universe. A new underground laboratory will offer opportunities to answer some of these questions by enabling a new generation of experiments on neutrinoless double beta decay, solar neutrino physics, supernova neutrino physics, dark matter, and the measurement of cross sections of astrophysical reactions.

Several of our most fundamental questions about neutrinos could be resolved if neutrinoless double beta decay were to be observed. The oscillation results define clearly the sensitivity needed in the next generation of double-beta-decay experiments, namely, the ability to measure masses of 10–50 meV. To reach such sensitivities requires these next-generation experiments to be massive and to be built deep underground, in ultraclean laboratories. Although no double-beta-decay experiments are currently running in the U.S., a number of U.S. groups are developing next-generation experiments, with the intent to start underground prototype measurements in 2002.

The present generation of solar and supernova neutrino detectors—together with Borexino, KamLAND, MiniBooNE, and other experiments now being readied—will more precisely determine neutrino masses and mixing angles in the next few years. Essential to this effort will be new experiments focusing on the lowest-energy neutrinos produced by proton-proton fusion in the solar core: The flux of these neutrinos is precisely constrained by the solar luminosity. By measuring the flux and type (electron or muon/tau) of these neutrinos when they arrive at the Earth, stringent new limits on neutrino mixing and on the existence of new neutrino states can be determined.

Several U.S. groups are currently engaged in intensive research and development focused on a number of different detector options. All require locations deep underground to avoid interference from cosmic rays. It is expected that one or more of these proposals will be submitted for funding within the next year.

In supernovae many of the frontier questions of nuclear physics converge. How does the core-collapse process work and culminate in an explosion? Where are the heavy elements made, and what role do neutrinos play in controlling the nuclear chemistry of this synthesis? Can we extract information from the neutrino flux on the nature of the dense nuclear matter in neutron star cores, or on the gravitational physics that governs neutron star or black hole formation? Supernova neutrino detection is a key component of the "supernova watch" program involving gravitational-wave detectors and optical telescopes. Because supernovae are rare events in our galaxy, occurring roughly once every 30 years, the establishment of long-term "supernova neutrino observatories" requires deep sites of the type provided by dedicated underground laboratories, where access and stability can be guaranteed for decades.

Nuclear astrophysics also has a stake in the establishment of a deep, dedicated underground laboratory. Cosmic-ray backgrounds interfere with measurements of nuclear reactions of astrophysical interest, which must be done at very low energies where rates are exceedingly low. A high-intensity, low-energy, pulsed heavy-ion accelerator allowing inverse kinematics experiments underground would be able to address a number of fundamental questions: Do we understand the nuclear physics reactions that power the stars? What is the influence of nuclear structure and nuclear reactions on the evolution, energy generation, and time scales in stars and in stellar explosions? How did our galaxy evolve to make the heavy elements we see today in our solar system?

An underground laboratory will also address a number of other issues, many with strong connections to nuclear physics. It will allow new experiments on atmospheric neutrinos and nucleon decay, long-baseline neutrino oscillation experiments, and the development of innovative applications of precision radioassay. It will also offer opportunities for studies in fields with less direct connections to nuclear physics, such as microbiology and geosciences.

The remaining question is, Why a new underground lab in the U.S.? The underground laboratories in Europe and Japan have proven very successful. Italy's Gran Sasso Laboratory, created to foster underground experiments in Europe, has become a major center, encouraging new ideas in underground physics and drawing researchers from across Europe, Asia, and the U.S. In Japan, the Kamioka proton-decay experiment, contemporaneous with the U.S. IMB experiment in the Soudan mine, was followed by SuperKamiokande, an effort that has produced profoundly influential solar and atmospheric neutrino discoveries. Both of these laboratories are currently fully subscribed, and several current experiments have thus sought space in less ideal underground environments. More important, however, is the modest depths of these laboratories: Kamiokande is at 2700 m (water equivalent), while Gran Sasso is at 3800 mwe. Gran Sasso was built 20 years ago, when the sensitivities and thus the shielding requirements of experiments were much less than they are today. Because of Kamioka's shallow depth, the solar neutrino physics that the KamLAND detector in Japan hopes to extract will be limited by cosmogenic radioactivity. The SNO experiment could not have been successfully mounted at depths as shallow as Gran Sasso or Kamiokande.

In short, current facilities are inadequate to answer some of the most perplexing questions facing the nuclear science community. Therefore, motivated by the discovery potential of the next generation of ultrasensitive neutrino experiments, the U.S. nuclear physics community is committed to developing NUSL. Such a facility will host international collaborations and will become the preeminent center in the world for doing underground science. The broad range of scientific fields represented and the cutting-edge research conducted there will offer learning opportunities for students at all levels (from K–12 to postdoctoral) in many academic disciplines, as well as excellent outreach opportunities to the American public. NUSL will provide specialized low-background facilities, concentrated technical expertise and knowledge, economies of scale, and the synergistic interactions among scientists from different fields so crucial to discovery.

The Homestake mine in South Dakota, which ceased operating as an active gold mine at the close of 2001, offers an ideal location for NUSL, with available experimental sites between 2100 and 7200 mwe. The existing infrastructure at the site includes massive shafts and hoist engines, sophisticated ventilation and air conditioning systems, communications and fiber-optics systems, and a skilled force of miners, engineers, and geologists. A proposal for the development of NUSL at Homestake has been submitted to the NSF, and efforts are under way for the state of South Dakota to assume ownership of the mine.

Building on Success: The CEBAF 12-GeV Upgrade

RECOMMENDATION 4

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

The 12-GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

Almost two decades have passed since the parameters of CEBAF were defined. During that period, the picture of how strongly interacting matter behaves has evolved dramatically, thus posing whole new classes of experimental questions best addressed by a CEBAF-class machine operating at higher energy. Fortunately, favorable technical developments, coupled with foresight in the design of the facility, make it feasible to triple CEBAF's beam energy from the initial design value of 4 GeV to 12 GeV (thus doubling the *achieved* energy of 6 GeV) in a very cost-effective manner. The cost of the upgrade is about 15% of the cost of the initial facility. Doubling the energy of the accelerator has three major motivations, the first two of which are "breakthrough" opportunities to launch programs in completely new areas of research.

First, the higher beam energy will allow us to cross the thresholds for the production of states that are not currently accessible with CW beams. A prime example is the spectroscopy of "exotic mesons," which will provide the data needed to determine whether the origin of quark confinement lies in the formation of QCD flux tubes. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations require that these states exist in the accessible mass regime and demonstrate that the levels and their orderings will provide experimental information on the mechanism that produces the flux tube. Tantalizing experimental evidence has appeared over the past several years for both exotic hybrids and gluonic excitations with no quarks (glueballs). Through simple spin arguments, photon beams acting as virtual vector mesons are expected to be particularly favorable for the production of exotic hybrids. A definitive experiment to map out the spectrum of these new states required by the confinement mechanism of QCD will be possible at 12 GeV. These programs will be carried out in a new "photons only" experimental area, Hall D.

Equally important, the higher energy (coupled with the CW beam and appropriate detectors) will open the door to the exploration, by fully exclusive reactions, of regions of high momentum and high energy transfer where electron scattering is known to be governed by elementary interactions with quarks and gluons, not with hadrons. The original CEBAF energy did not allow full access to this critical regime, whereas at 12 GeV, researchers will have access to the entire "valence quark region." This will be the first experimental facility that can measure the deep exclusive scattering (DES) cross sections in the kinematical regime where the three basic ("valence") quarks of the proton and neutron dominate the wave function. The valence quarks play a big role over a large part of the nucleon, but it is only in this newly accessible regime that there are no significant contributions from more complicated components to the nucleon wave functions. With the energy upgrade, it will be possible to map out the quark distribution functions in the entire valence quark regime with high precision, which will have a profound impact on our understanding of the structure of the proton and the neutron. However, these structure functions are probabilities, not wave functions, and until recently the attempt to determine the quark-gluon wave functions of the nucleons has been seriously handicapped by the lack of a rigorous framework for making a connection between experimental measurements and these wave functions. The theoretical discovery of generalized parton distributions (GPDs) and their connection to certain totally exclusive cross sections have made it possible in principle to rigorously map out the complete nucleon wave functions themselves. The 12-GeV upgrade will make it possible to explore this new DES domain. This will allow exploration of the complete quark and gluon wave functions of the nucleons through measurements of quark momentum distributions, as well as through the novel framework of GPDs.

Finally, in addition to these qualitative changes in the physics reach of CEBAF, 12 GeV will also allow important new research thrusts in Jefferson Lab's existing research campaigns, generally involving the extension of measurements to substantially higher momentum transfers (and thus to correspondingly smaller distance scales). An example of this is the measurement of the pion elastic form factor, one of the simplest quark systems. With the larger momentum transfers available, it should be possible to observe the transition from the strong QCD of confinement to perturbative QCD. Another example is the ability to probe the limits of the nucleonic picture of short-range correlations (SRCs), whose kinematics were first reachable at CEBAF at 4–6 GeV. The upgrade provides unique opportunities for measuring quark distributions over an even broader range of x and Q^2, thus investigating the parton structure of bound nucleons. At this upgraded energy, we also cross the threshold for charmed-quark production. Another benefit is that most experiments that are approved to run at a currently accessible momentum transfer can be run more efficiently at higher energy.

The success of the original CEBAF design is one of the key features that make a cost-effective upgrade possible. First, the installed five-cell superconducting RF cavities have exceeded their design acceleration gradient of 5 MV/m by more than 2 MV/m and their design Q-value by a similar factor. Furthermore, seven-cell cavities have now been designed that are significantly more powerful than the original design. Accordingly, 12 GeV can be reached by adding ten new modules in space available in the linac tunnels. However, this technological advance would not be so readily applied if it were not for the fact that the "footprint" of the CEBAF accelerator was, with considerable foresight, designed so that the recirculation arcs could accommodate an electron beam of up to 24 GeV.

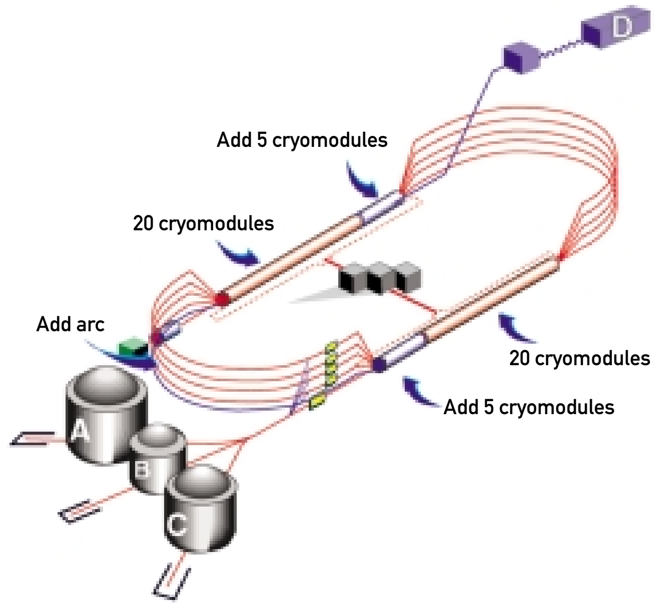


Figure 5.3. Elements of the CEBAF upgrade. Increasing the beam energy at CEBAF from 6 to 12 GeV requires upgrades in four areas: (i) additional accelerating power, (ii) stronger magnets in the recirculation arcs, (iii) an upgraded cryoplant, and (iv) one additional recirculation arc. The higher-energy electrons can be directed to a new experimental area, Hall D.

The basic elements of the CEBAF upgrade can thus be seen in Figure 5.3. The upgrade utilizes the existing tunnel and does not change the basic layout of the accelerator. There are four main changes: (i) additional acceleration in the linacs, as outlined above; (ii) stronger magnets in the recirculation arcs; (iii) an upgraded cryoplant; and (iv) the addition of a tenth recirculation arc, permitting an additional "half pass" through the accelerator (to reach the required 12-GeV beam energy), followed by transport to the new hall that will be added to support the meson spectroscopy initiative.

The timely completion of the CEBAF upgrade will allow Jefferson Lab to maintain its world leadership position, as well as to expand that leadership into new areas. The program of exotic mesons in Hall D is viewed by many as the definitive search for these states, and Jefferson Lab's polarized photon beam will be the unique instrument to carry it out. The complete mapping of the nucleon wave functions is both interesting and of significant importance in other branches of nuclear physics, where these wave functions are important input to understanding higher-energy phenomena.

Maintaining Competitiveness: Other New Initiatives

The continuing vitality of nuclear science demands a constant flow of new ideas, both theoretical and experimental. Among such ideas are proposals tied to new facilities, new instrumentation, and significant upgrades to existing experiments. Even under the tightest budget constraints, a fraction of the nuclear physics budget must be set aside to provide the flexibility to pursue new initiatives. The following initiatives are not explicitly encompassed in the four major recommendations of this Plan. Some may be implemented, nonetheless, in the context of facility operations and improvements, or in recognition of their great promise. Others may be promoted to the status of strong recommendations in a subsequent long-range plan. All are worthy of continuing attention as the field evolves in the coming years.

Luminosity upgrades: RHIC II. RHIC is currently the most flexible facility in the world for the study of nuclear collisions at very high energies. Initial operation has validated the facility's design, and the peak luminosity for gold-gold collisions has exceeded the design average luminosity. Nonetheless, extensive benefits to RHIC science would result from an upgraded facility (RHIC II) designed to provide luminosities significantly in excess of the design values. A noteworthy example is the study of the "–onium" mesons that consist of bound heavy quark-antiquark pairs. To make a significant advance in this realm of research, an order-of-magnitude increase in RHIC luminosity is required. Photon-jet coincidence measurements provide another example of an essential probe that is limited by the available luminosity.

Initial steps toward higher luminosities are possible with the existing RHIC facility. Doubling the number of bunches from 55 to 110 in each ring and increasing beam-focusing will provide a fourfold increase in luminosity, which is thought to be achievable without increased funds. The major technical issue involved in this first stage of upgraded operations is the optimization of corrector elements in the interaction triplets, to account for the larger beam size induced by the stronger focusing.

Further progress will require addressing the emittance growth due to intrabeam scattering. This is the dominant limitation for heavy ions, where the Coulomb repulsion within bunches leads to a rapid decrease in the luminosity during a store. Electron cooling of the ion beams provides an elegant solution to this problem. A comoving beam of electrons (which, for gold ions at 100 GeV per nucleon, implies electrons at approximately 50 MeV) is able to exchange momentum with the ions and thus reduce the growth in longitudinal phase space that would otherwise occur. Current studies, performed in collaboration with the Budker Institute of Nuclear Physics (Novosibirsk), are centered on designs based on an energy-recovery superconducting linac for the electrons, which is based in turn on the very successful work for the free electron laser (FEL) at Jefferson Lab. The 10-mA beam current required for RHIC cooling is comparable to the 5 mA already achieved for the Jefferson Lab FEL. The addition of electron cooling to the RHIC facility will increase the luminosity by another factor of 10, producing a final luminosity that will be a factor of 40 higher than the design value for gold-gold collisions. For protons, where intrabeam scattering is not a major concern, the cooling may be applied at injection energies, resulting in 25-fold luminosity increases over design values.

Continued progress towards a functioning RHIC II, to be available on a time scale relevant to the ongoing scientific effort, will be possible only via a vigorous program of R&D focused on electron cooling and electron accelerator options, leading toward formal design and construction. Corresponding upgrades will be required for the existing experiments, particularly in the areas of data acquisition and triggering. The associated costs are incremental in comparison to the large investment already made in the RHIC program, while the benefits are significant, ranging from new physics signals to greatly increased efficiency of operation.

The Electron-Ion Collider. The Electron-Ion Collider (EIC) has been proposed as an essential tool for research into the fundamental quark-gluon structure of matter. Its central scientific goal is to address some of the key questions in nuclear physics: What is the structure of matter in terms of its quark and gluon constituents? How do quarks and gluons evolve into hadrons via the dynamics of confinement? How do quarks and gluons reveal themselves in the structure of atomic nuclei? Can nuclei be used to study partonic matter under extreme conditions? To what accuracy is QCD the exact theory of the strong interaction?

To build upon the insights gained from current research, the EIC will be necessary by the end of this decade. The EIC design characteristics have been shaped by three decades of experimental work at high-energy physics facilities; these characteristics include the following:

- A facility for colliding electrons (or positrons) with protons and with light and heavy nuclei
- A high luminosity: $L > 10^{33}$ cm^{-2} s^{-1} per nucleon
- A wide range of center-of-mass energies: E_{CM} = 15–100 GeV
- The capability for polarization of electron and proton spins
- Preferably two interaction regions with dedicated detectors

Two classes of machine designs for the EIC have been considered: (i) a ring-ring option where both electron and ion beams circulate in storage rings and collide at a number of interaction points and (ii) a ring-linac option where a linear electron beam is incident on a stored ion beam. The latter configuration has been considered at Brookhaven, where the RHIC ion beam could be used and center-of-mass energies up to 100 GeV should be possible. The ring-ring option at a center-of-mass energy of 30 GeV has been considered by an MIT-Bates–Budker collaboration.

The scientific case for the EIC, as well as preliminary machine designs, were favorably endorsed by the community during the past year. There was a strong consensus to pursue R&D over the next three years in the areas of electron cooling of the ion beam, self-polarization of the electron beam, polarized electron sources, and detector integration into the interaction region.

A 4π Gamma-Ray Tracking Array. The detection of gamma-ray emissions from excited states in nuclei plays a vital and ubiquitous role in nuclear science experiments, and each advance in gamma-ray detector technology has been accompanied by significant insights into the nucleus. At the time of the 1996 long-range plan, it was realized that large gains in resolving power (see Figure 5.4) would be possible by applying the new concept of gamma-ray energy tracking to a 4π detector shell consisting of electrically segmented germanium crystals. This major advance in technology promises to revolutionize gamma-ray detector design and will enable a new class of high-resolution gamma-ray exper-

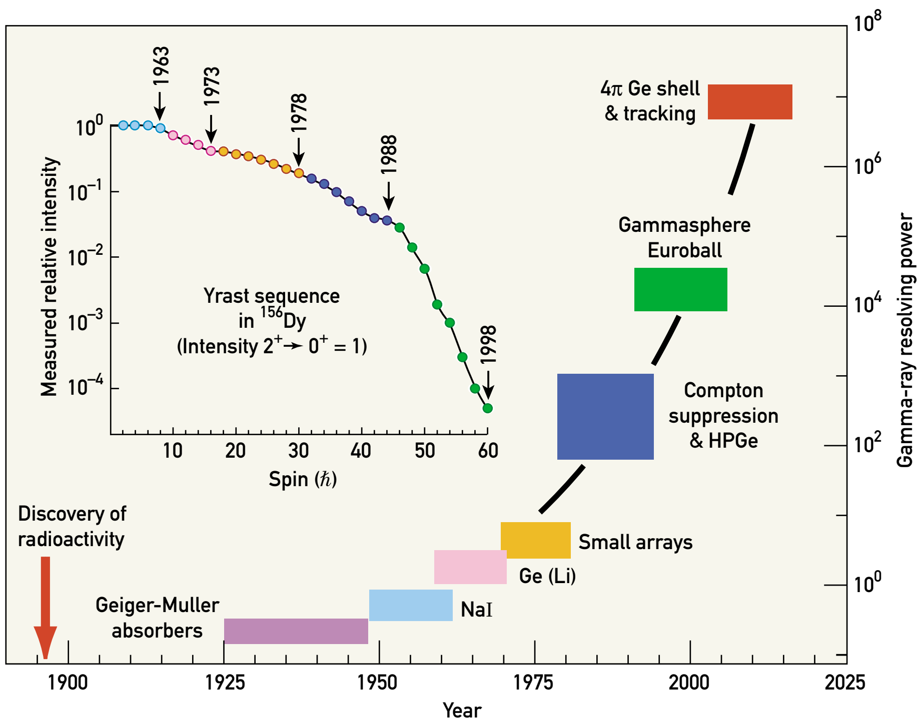


Figure 5.4. Evolution of gamma-ray detection technology. The large gain provided by a 4π tracking array, such as GRETA, is clearly shown. The calculated gamma-ray resolving power is a measure of the ability to observe the faint emissions from rare and exotic nuclear states. This is illustrated in the top left-hand insert, which indicates the strong inverse relationship between resolving power and the experimental limit for observing excited states in a typical rare-earth nucleus.

iments at several existing stable- and radioactive beam facilities, as well as at RIA.

In a gamma-ray tracking detector, the energy and position of each gamma-ray interaction point is obtained by using germanium crystals with a high degree of electrical segmentation. The path of a given gamma ray can be "tracked," and the full gamma-ray energy is obtained by summing the detected interactions belonging to that gamma ray. Tracking also provides the position of the first interaction to within 1–2 mm, allowing high-resolution gamma-ray studies of nuclei produced in reactions at high recoil velocity, where Doppler broadening is significant. Other key design benefits of a highly segmented germanium array include the ability to handle high count rates and high multiplicities, to obtain linear polarizations, and to pick out low-multiplicity events hidden in a high-background environment.

A detector design for a 4π array called GRETA (Gamma-Ray Energy Tracking Array) was featured in the 1996 long-range plan. It contains about 100 coaxial germanium crystals, each segmented into 36 portions and arranged in a highly efficient 4π geometry. GRETA will have a calculated resolving power 100–1000 times that of Gammasphere at a similar overall cost. Since the 1996 plan, substantial R&D has been carried out, leading to proof-of-principle demonstrations in all the key areas:

- Highly segmented germanium detectors have been successfully manufactured (a 36-segment detector has been used for testing purposes for several years).
- Pulse-shape digitization and digital signal-processing methods have been developed to determine the position, energy, and time of gamma-ray interactions (position resolutions of better than 2 mm have been achieved).
- Tracking algorithms have been developed that are capable of identifying the interaction points of a particular gamma ray.

A detector technology based on segmented planar (strip) germanium detectors is also being pursued. Arranged into a boxlike configuration, the GARBO (Gamma-Ray Box) design will be especially efficient for low-energy gamma rays and x-rays, and is an important complementary detector system to the 4π coaxial detector array. In addition, a system of eighteen 32-fold segmented germanium detectors has just been completed for experiments using fast exotic beams. It represents a significant step toward a full 4π germanium tracking array.

The physics justification for a 4π tracking array that would build on the success of Gammasphere is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions.

Exploiting cold neutrons: The Neutron Initiative. Studies of the static properties and beta decay of the neutron offer a sensitive means to test fundamental symmetries and to elucidate the structure of the weak interactions. In the past, most of the experiments with neutrons have involved neutron beams from reactors. Such experiments have typically been limited by the high backgrounds at reactors and by the difficulty of measuring the beam polarization precisely. By employing intense beams of pulsed cold neutrons and by using ultracold neutrons (UCNs), this experimental thrust can be substantially enhanced.

The use of pulsed cold neutron beams at spallation sources allows for a clear separation of the signal from unwanted backgrounds. In addition, one can polarize the neutrons with great precision by passing them through a cell that contains optically polarized ^{3}He. Experiments are now under way with pulsed cold neutrons at LANSCE. Furthermore, it will be possible in the future to take advantage of the SNS, now under construction at Oak Ridge, because it will produce beams of pulsed cold neutrons an order of magnitude more intense than at LANSCE, with a dramatic improvement in the signal-to-noise ratio. The neutron-scattering community at the SNS has agreed to provide a cold neutron beam dedicated to nuclear physics measurements. This opportunity will represent a highly leveraged use of nuclear physics funds to carry out world-class experiments with neutrons.

In a second thrust, tremendous advances have been made in the use of superthermal UCN sources that far surpass the capability of the UCN source at the ILL reactor in Grenoble, France—currently the most intense in the world. These sources take advantage of the fact that the UCN production rate in a cryogenic medium can be made much greater than the loss rate. Two types of superthermal UCN sources have been identified: One produces UCNs in superfluid liquid helium at <1 K, the other in solid deuterium at 5 K. The "helium" source has a relatively low production rate, but it also has an extremely low loss rate, allowing the accumulation of a very high density of UCNs in a bottle over a period of a few hundred seconds. The "deuterium" source has a very high production rate but also has a significant loss rate, making it best suited to providing a highly intense flow of UCNs. Prototypes of both sources have performed as expected. To exploit these innovations, even more intense UCN sources are needed. In the case of the "helium" source, this goal could best be achieved using a cold neutron beam at the SNS, whereas for the "deuterium" source, a high-intensity national UCN user facility could be built at any of several existing accelerators. Such sources would provide the opportunity to search for new physics that is both complementary to and comparable in sensitivity to experiments at the next generation of high-energy accelerators.

Improving computational nuclear physics: The Large-Scale Computing Initiative. Many forefront questions in contemporary theoretical nuclear physics and nuclear astrophysics can only be addressed using computational methods. For example, understanding the confinement of quarks and the structure of hadrons requires lattice QCD calculations; solving the quantum many-body problem for nuclei requires quantum Monte Carlo calculations; and understanding the origin of the elements in supernova explosions requires multidimensional simulations. Theoretical work on these questions is crucial if we are to realize the full physics potential of the investments made at Jefferson Lab and RHIC and the new investments recommended for RIA and the underground lab. Advances in computational physics and computer technology represent great opportunities for breakthroughs in nuclear physics and nuclear astrophysics. To exploit these opportunities, dedicated facilities must be developed with world-leading computational capabilities for nuclear physics research.

Lattice QCD is crucial for answering fundamental questions in strong-interaction physics, and it is widely recognized that definitive lattice QCD calculations require multi-teraflops resources—resources now available at reasonable cost. In addition, successful nuclear physics programs at Jefferson Lab and RHIC urgently need to make connection to QCD. An aggressive and dedicated effort is needed for the U.S. to regain a competitive edge—an edge that has been lost to Japan and Europe—in using lattice QCD to understand hadronic physics. The nuclear science component of an internationally competitive lattice effort requires dedicated facilities providing sustained performance of 0.5 teraflops by 2002, growing to 15 teraflops by 2005.

On a second front, multidimensional supernova simulations are essential to understand the origin of heavy elements and the mechanism of supernova explosions. Although significant progress has been made in such large-scale numerical simulations, many shortcomings remain. For example, current one-dimensional models generally fail to "explode," and in current multidimensional models, a variety of phenomena—neutrino transport, convection, rotation, magnetic fields, and general relativity—are inadequately modeled. A particularly urgent need in this field is investment in young scientists with multidisciplinary skills who can attack the neutrino transport, hydrodynamics, nuclear science, and computer science issues associated with supernova modeling.

In a third area, quantum many-body methods open the door to the precise calculation of nuclear structure in terms of the interactions among the basic constituents—protons and neutrons. Understanding nuclear structure and understanding nuclear reactions are two of the most important goals in nuclear science. And recent progress has been impressive. However, calculations continue to depend critically on large-scale computational resources. For instance, current quantum Monte Carlo calculations of $A = 8$ nuclei require about 500 node-hours, with each node operating at 160 megaflops. With a teraflops computer, ^{12}C can be solved in a matter of hours. Ultimately, with new algorithms currently being developed and tested, accurate calculations for many nuclei in the chart of the nuclear isotopes, and for dense nucleonic matter, may become possible.

The DOE has recognized the important role of computational tools in nuclear physics and nuclear astrophysics. Through its SciDAC initiative, it has made initial substantial grants for software development in lattice QCD and supernova simulation. The computational nuclear physics and nuclear astrophysics communities urge continued SciDAC funding for these areas and are committed to pursuing additional SciDAC funding. They further hope that a combination of topical centers that exploit cost-effective features for specific applications and funding for general-purpose machines at NERSC will meet most of the community needs.

ORLaND: Snaring terrestrial neutrinos. The SNS at Oak Ridge will be not only the world's most intense pulsed neutron source, but also the world's most intense pulsed source of intermediate-energy neutrinos. This provides the neutrino research community with a unique opportunity to build a laboratory in which a number of state-of-the-art neutrino measurements could be performed. This is particularly cost-effective, because none of the construction or operations costs of the SNS accelerator complex will be borne by the neutrino facility.

A by-product of the operation of the SNS is the production of about 10^{15} neutrinos per second in each of three flavors (ν_e, ν_μ, and $\bar{\nu}_\mu$). The pulsed time structure of the SNS-produced neutrinos will essentially eliminate cosmic-ray-induced background and will allow significant separation of the neutrino flavors produced. The neutrinos produced at the SNS will also have well-characterized spectral shapes and known abundances, and $\bar{\nu}_e$ neutrinos will be strongly suppressed, relative to the other three. The neutrino spectra will cover an intermediate-energy range up to about 55 MeV—the same energy range of interest in studies of supernova explosions. This energy range is not accessible either at reactors, where neutrino energies are typically below 10 MeV, or at most accelerators, where higher energies dominate.

The importance of neutrino physics to our fundamental understanding of nature makes a compelling case for a high-intensity, pulsed neutrino facility. With the nucleus as a laboratory, neutrino experiments can be expected to revise and extend our current understanding of the Standard Model and can serve to probe the substructure of the proton and the neutron, as well. Neutrinos are key players in the dynamics of exploding supernovae and in the ignition of the primal *pp* chain of stellar burning. Intrinsic neutrino properties, such as their mass, influence the dynamics of the universe through their possible contribution to dark matter. The question of neutrino oscillations between flavor states is intimately related to our understanding of the physics of supernova evolution and to the structure of the neutrino mass matrix.

In light of these opportunities, the Oak Ridge Laboratory for Neutrino Detectors (ORLaND) has been proposed. It would consist of a concrete "bunker" large enough to accommodate one very large (2000 ton) detector and five or six smaller special-purpose detectors, with an overburden of 30 m (water equivalent) to further reduce the background from cosmic rays.

6. Resources: Funding the 2002 Long-Range Plan

Background

The joint DOE/NSF charge to NSAC requested that the long-range plan identify the "most compelling scientific opportunities to be addressed in the next decade and the resources that will be needed to address them." NSAC was asked to consider two funding scenarios, one in which a world-leadership position in nuclear physics research is maintained, and one in which funding is maintained at current levels, with adjustment for inflation, throughout the coming decade. Fiscal year 2001 is taken as the baseline for this exercise and budgets are projected into the out-years in constant 2001 dollars.

Guided by the NSAC long-range planning process, the DOE and the NSF have invested in new forefront capabilities that place U.S. nuclear science in a world-leading position. To achieve this goal within tight financial constraints, painful choices and program reductions have been necessary. In this context, the long-range plans have proved to be invaluable to the nuclear science community, to the funding agencies, and to Congress, since they have provided the framework for building consensus on major initiatives and for meeting the difficult challenges of priority-setting.

Figure 6.1 summarizes the funding trends over the past decade, in constant fiscal year 2001 dollars, for the combined DOE and NSF budgets. Since 1992, total funding for nuclear physics from these two agencies has decreased by about 25% when adjusted for inflation. Nevertheless, during this period, the nation has made major investments in new facilities, with the construction of RHIC and CEBAF and the upgrade of NSCL. However, the current budget level is jeopardizing our ability to reap the scientific benefits from these recent investments, and it severely reduces the range of opportunities for new discoveries. The funding subcategories for research, facility operations, and construction, shown in Figure 6.1, demonstrate that during the past decade inflation-adjusted support for research and facility operations declined dramatically to allow the major construction projects to meet their milestones. Now that the new facilities are complete, there are insufficient funds to operate them at an appropriate level. The decline in research funding has also had a significant impact. Support for research at universities is typically highly leveraged, so the decline in research funding provided by both the DOE and the NSF has had a particularly adverse effect on the nation's nuclear science research portfolio and on the training of the next generation of scientists.

These significant reductions occurred during a period that saw unprecedented growth in federal support for biomedical research. In recognition of the need to restore balance to the nation's science portfolio, a consensus has now emerged that a higher priority be given to increased funding for the physical sciences. Nuclear science is an essential component of this portfolio.

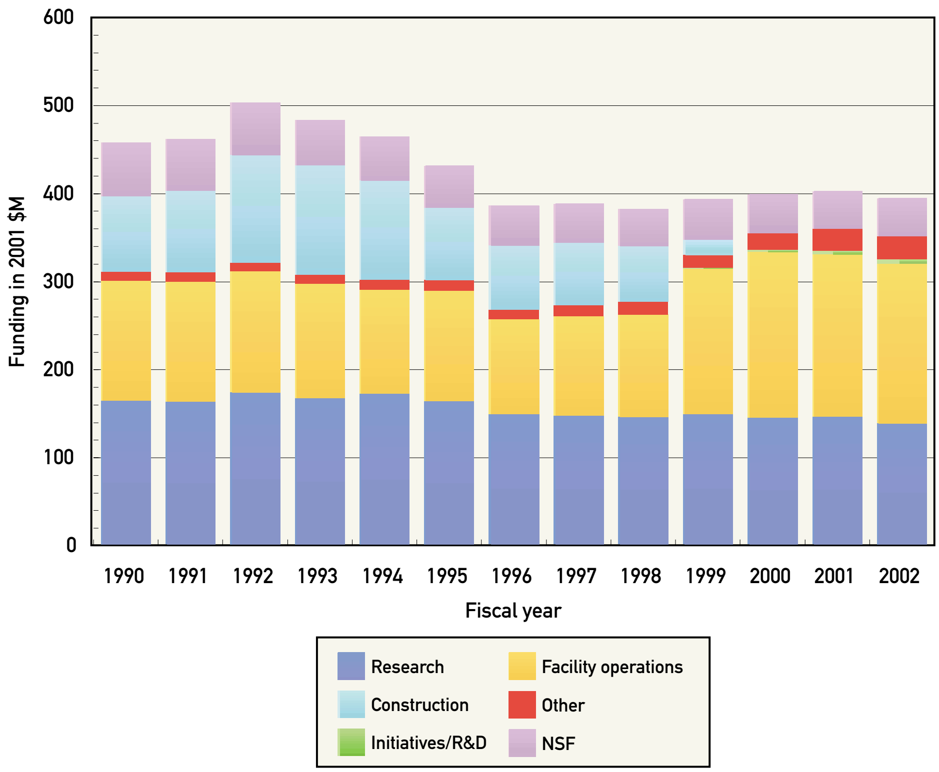


Figure 6.1. Funding for nuclear science, 1990–2002. The chart shows total DOE and NSF funding in fiscal 2001 dollars. All categories except "NSF" reflect DOE funding only. Since the 1992 peak, total funding has decreased by about 25%.

Resources for the Current Program

Since publication of the 1996 long-range plan, the U.S. nuclear science community has successfully completed the construction of RHIC and the upgrade of the NSCL—major new investments for the field. As indicated above, while these investments provide the nation with new world-leading capabilities and outstanding opportunities for breakthrough discoveries, they have required major sacrifices, and the current budget does not adequately support either facility utilization or research at universities and national laboratories.

The DOE is the source of approximately 90% of federal funding for nuclear science, including support for the two large world-class nuclear science facilities, CEBAF and RHIC, as well as several smaller facilities at universities and national laboratories. Figure 6.2 indicates the distribution of funding for nuclear physics in the DOE for fiscal year 2001.

After adjustment for inflation, the DOE nuclear physics budget only recently reached the minimum level established in guidance given to NSAC in 1995 for the previous long-range plan. Furthermore, funding for important stewardship responsibilities at the DOE laboratories has grown substantially in recent years, increasing pressure on other areas of the budget. Thus, the objectives of the carefully prepared 1996 plan have not been met, as facilities have been operated at reduced levels, and important research opportunities have been delayed or even lost.

The NSF nuclear physics budget plays a crucial role in supporting the high-quality nuclear science research portfolio of the nation. Investigators compete for these NSF funds on a regular basis by means of peer-reviewed proposals. The funds provide research support for individual investigators at universities and operating support for several university-based laboratories, including two user facilities (NSCL at Michigan State and IUCF at Indiana). The NSF supports nearly half of all university-based nuclear scien-

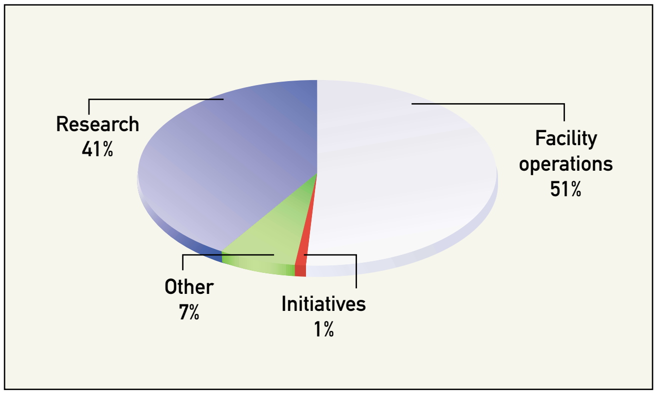


Figure 6.2. Distribution of DOE funding for nuclear science in fiscal year 2001. Total funding was $260.1 million. The category "Other" refers to items such as the SBIR program and stewardship functions at the national laboratories.

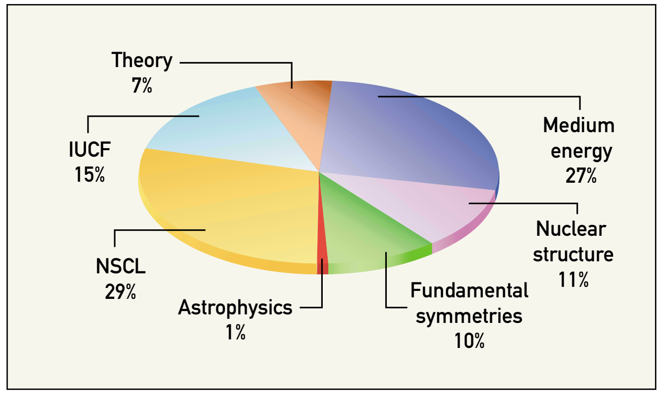


Figure 6.3. Distribution of NSF funding for nuclear science in fiscal year 2001. Total funding was $42.6 million.

tists, many of whom play leading roles at the nuclear science user facilities, including those supported by DOE.

Figure 6.3 indicates the distribution of NSF funding provided by the fiscal year 2001 budget. Forty percent of the budget provides for the operation of major facilities located at universities, with the remainder directly supporting the research of university-based investigators. The nuclear physics budget of the NSF has been under enormous pressure in the past several years. Many well-established university research groups and individual investigators, as well as promising young researchers, have submitted high-quality proposals, only to have them inadequately funded or even turned down, despite excellent reviews. In addition, in 1996 a decision was made that the IUCF's Cooler ring would be phased out following a period of full operations, in spite of its continuing productivity as a user facility for nuclear science. The existing proposal pressure for NSF is sufficiently high to warrant significant increases in the NSF nuclear physics budget.

Funding Scenarios for the Long-Range Plan

In response to the charge, this Plan identifies the resources required to realize both the expected scientific potential of the world-class facilities that have been constructed in the past decade and the other exciting scientific opportunities described in this report.

The highest priority of the field is increased funding for research and facility operations. A 15% growth in funding beyond that needed to maintain a constant level of effort is essential to provide for effective utilization of the nation's nuclear science facilities, to allow university-based scientists and their students to carry out their research in a timely way, to effectively train the next generation of nuclear scientists, and to revitalize research in nuclear theory. Such an increase would also provide for the modest R&D required as the basis for future development of the nation's nuclear science facilities. Finally, the proposed increase would provide the funding needed to develop innovative new instrumentation and to investigate select new initiatives, in response to new ideas that cannot be anticipated years in advance. A capacity for such responsiveness is essential if we are to maintain the vitality of the field, and it greatly enhances the scientific, technological, and educational returns on the nuclear science investment. We propose that this 15% increase be implemented within a three-year period.

The tragic events of September 11, 2001, occurred during the development of this Plan, and we recognize that the nation's priorities have changed. Nonetheless, we believe that this funding request is a needed and responsible one for an area of basic research that has important strategic ramifications.

Our highest priority for new construction, the Rare Isotope Accelerator (RIA), is a bold new concept that will result in the most advanced capability in the world for producing and studying isotopes at the limits of nuclear existence. Research at RIA will explore the often unexpected properties of these exotic isotopes, address basic questions about the origin of the elements and the evolution of stars, and pursue cross-disciplinary research relevant to biomedicine and national security. RIA is a decadal project that requires substantial additional funding above the present nuclear physics base. Maintaining the base is essential in order to maintain the U.S. leadership position at CEBAF and RHIC. While a modest redirection of funds toward RIA construction is possible by closing some of the existing low-energy accelerators, an immediate action of this kind may not be in the best long-term interest of the nation, as these machines are critical to the pursuit of productive lines of current research and promising new directions. Moreover, these facilities are needed for training the next generation of scientists, both for work at RIA and for meeting national needs in high-technology areas such as medicine, stockpile stewardship, and energy production.

The world's deepest underground science laboratory, proposed in this Plan, will provide a compelling opportunity for nuclear scientists to explore fundamental questions in neutrino physics and astrophysics. This project has been proposed to the NSF as a major new initiative. Incremental funding has been requested for construction, operations, and the facility's future experimental program.

We have also strongly recommended the upgrade of CEBAF to 12 GeV as soon as possible. This upgrade is critical for our continued leadership in the experimental study of hadronic matter and will require investments in the CEBAF accelerator and experimental facilities.

A funding scenario consistent with these recommendations is shown in Figure 6.4. This profile reflects the needed 15% growth in the base (some of which appears in the category "Small initiatives"), distributed over three fiscal years, 2003–05. With this readjusted base, effective facilities operations and research at universities will become possible, and a number of modest new opportunities can be realized. As shown in Figure 6.4, additional funding is needed for the CEBAF upgrade, for the construction and operation of RIA, and for NUSL. (RIA is assumed to be a seven-year construction project beginning in fiscal year 2006 and with operations beginning in fiscal year 2012. We assume construction to begin on the CEBAF upgrade in fiscal year 2005, with an increment to Jefferson Lab operations beginning in fiscal year 2008.)

This projected funding picture shows an increase peaking at roughly 60% above a constant level of effort, then falling back to a "steady state" level a decade hence. The level of funding in 2013 would be higher than today, but is comparable to the level of funding that existed a decade ago (see Figure 6.1).

A funding level corresponding to the constant-effort budget scenario specified in the charge would obviously require major deviations from the trajectory mapped out for nuclear science in this Plan and in the 1996 long-range plan.

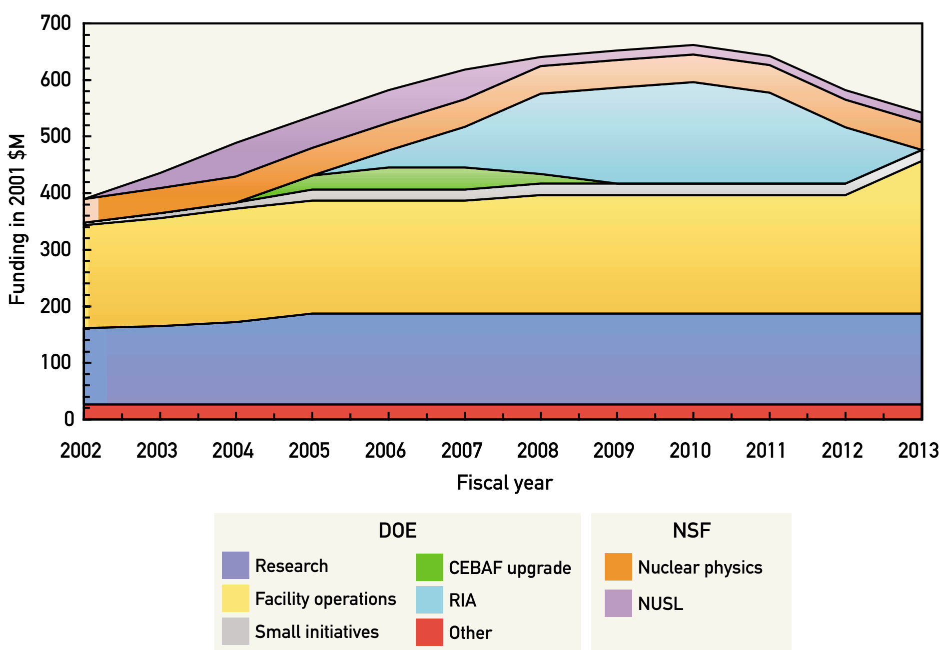


Figure 6.4. A funding scenario for fiscal years 2002–2013. The funding profile depicted would allow implementation of the four recommendations of the present Plan: adequate funding for research and facility operations, construction of RIA and NUSL, and the upgrade at CEBAF.

In a constant-effort scenario, the U.S. program in nuclear science would remain at a world-class level in a number of core areas, but many exciting opportunities would be missed. Termination of some first-rate research programs and losses in cutting-edge research would be required to implement the field's highest priorities—effective operation of the new facilities and improving support for research and training in the universities. In the long run, even more severe measures would be needed to create the flexibility required to pursue some selected, highly compelling new initiatives.

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.

Personnel Requirements

The charge to NSAC also requested information about the personnel needed to carry out the Plan. Currently, approximately 2000 U.S. researchers and about 1000 foreign scientists use U.S. research facilities. These researchers, both experimentalists and theorists, can be grouped into four large areas of research: relativistic heavy ions, medium-energy research (largely with electrons), nuclear structure and astrophysics, and fundamental properties and symmetries. Initiatives associated with the first two research categories will not require significant new personnel. The major initiatives associated with the third and fourth categories, RIA and NUSL, will draw from existing reservoirs of effort at other facilities, both in the U.S. and abroad. As has been the case in the past, we expect that exciting new facilities will attract new people and, in particular, new graduate students. On balance, however, we envision no major shortage of personnel, as some facilities will cease operation as new ones come on-line.

Concluding Remarks

This long-range plan for nuclear science aims at maintaining a world-leading program, as requested in the charge from DOE/NSF. It builds upon existing strengths and provides an appropriate return on the nation's recent investments by allowing timely realization of major scientific opportunities. If appropriately funded, U.S. nuclear science will make major advances and will deepen our understanding of the strongly interacting matter that makes up most of the visible universe. By funding cutting-edge research at universities, we will attract and train new generations of scientists who will continue to serve the nation in unique and important ways. In the coming decade, we can look confidently to nuclear science to make vital contributions to the nation's intellectual and material well-being and to the health and security of its citizens.

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

July 21, 2000

Dr. T. James Symons
Chairman
DOE/NSF Nuclear Science Advisory Committee
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

Dear Dr. Symons:

This letter requests that the DOE/NSF Nuclear Science Advisory Committee (NSAC) conduct a new study of the opportunities and priorities for U.S. nuclear physics research and recommend a long range plan that will provide a framework for coordinated advancement of the nation's nuclear research programs over the next decade. Previous NSAC Long Range Plans (LRP), in particular the 1996 LRP, are appropriate and important reference documents. Please submit an interim report containing the essential components of NSAC's recommendations to the Department of Energy (DOE) and the National Science Foundation (NSF) by April 15, 2001, and the final report by October 1, 2001.

Since the submission of the NSAC 1996 LRP, major investments at TJNAF/CEBAF, BNL/RHIC and MSU/NSCL, as well as at our other user facilities, have significantly expanded our national capabilities for nuclear physics research. Major detectors have been or are in the process of being implemented at both accelerator and non-accelerator facilities to exploit many promising opportunities. University research programs and facilities, including the Institute of Nuclear Theory, continue to play important and critical roles in the nation's nuclear physics program. These capabilities and the priorities in the national program today are a consequence of the nuclear science community's responsible and visionary strategic planning embodied in the previous NSAC LRP.

The new NSAC plan should identify the most compelling scientific opportunities to be addressed in the next decade and the resources that will be needed to address them. It is important that the priorities of the identified scientific opportunities be well articulated. The required resources should include both people (the investigator community) and tools (capitalizing on recent investments and investing for the future). To be most helpful, the plan should indicate what funding levels would be required (including construction of new facilities) to maintain a world-leadership position in nuclear physics research, and what the impacts and priorities should be if the funding available provides constant level of effort (FY 2001 President's Budget Request) into the outyears (FY 2002-2012).

As RHIC construction is now complete, it is timely that the community consider new major facilities to address emerging scientific opportunities. In the 1996 LRP, NSAC recommended construction of a "next generation ISOL-type facility" to be "constructed when RHIC construction is substantially complete." The plan should evaluate the scientific potential of the proposed Rare Isotope Accelerator and any other new proposed facilities in the broad context of the most compelling scientific questions, as well as the availability of existing and planned facilities, and establish priorities for new construction.

Your effort should lead to a coordinated long range plan for the synergistic DOE and NSF programs in nuclear physics, recognizing the different roles of the two agencies in building and operating forefront national facilities for users, in supporting university-based research, and in science education.

To maintain the U.S. position of leadership, the facilities available in other nations should be taken into consideration, and the new NSAC plan should point out the opportunities for increased cooperation with other countries on projects of mutual interest. An important dimension of your plan should be the role of nuclear physics in advancing the broad interests of society, and how mutually beneficial interactions with neighboring basic research disciplines, such as astrophysics, and with applied disciplines can be strengthened. The possible opportunities for nuclear physics research from the anticipated advancements in computing capabilities in the next decade should be addressed.

Education of young scientists is central to the mission of both agencies and is integral to any vision of the future of the field. We ask NSAC to articulate the importance of education in nuclear science to academia, to medicine, to defense, to industry, and to government. We ask further that NSAC analyze the effectiveness and appropriateness of current graduate programs in nuclear science in preparing future generations of scientists, to articulate the role that the nuclear science research community presently plays in addressing broad educational needs of national concern, including diversity issues, along with strategies for strengthening these roles in a way that makes optimal use of the resources of the community.

In the 1989 and 1996 LRP, the Division of Nuclear Physics of the American Physical Society (DNP/APS) was instrumental in obtaining broad community input by organizing town meetings of different nuclear physics sub-disciplines. The Division of Nuclear Chemistry and Technology of the American Chemical Society (DNC&T/ACS) was also involved. We encourage NSAC to exploit this method of obtaining widespread input again, and to further engage both the DNP/APS and DNC&T/ACS in laying out the broader issues of contributions of nuclear science research to society.

The agencies very much appreciate NSAC's willingness to undertake this task. As you recognize, NSAC's previous long range plans have played a critical role in shaping the nation's nuclear science research effort. Based on NSAC's laudable efforts in the past, we look forward to a new plan that can be used to chart a vital and forefront scientific program into the next decade.

Sincerely,

James F. Decker
Acting Director
Office of Science
Department of Energy

Robert A. Eisenstein
Robert A. Eisenstein
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

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Tom Bowles, *Los Alamos*
Daeg Brenner, *Clark University*
Wit Busza, *MIT*
Larry Cardman, *Jefferson Lab*
Rick Casten, *Yale University*
Gordon Cates, *University of Virginia*
Jolie Cizewski, *Rutgers*
Paul Fallon, *Berkeley Lab*
Bradley Filippone, *Caltech*
Stuart Freedman, *UC Berkeley/ Berkeley Lab*
George Fuller, *UC San Diego*
Gerry Garvey, *Los Alamos*
Don Geesaman, *Argonne*
Konrad Gelbke, *Michigan State University*
Charles Glashausser, *Rutgers*
Thomas Glasmacher, *Michigan State University*
Tim Hallman, *Brookhaven*
Wick Haxton, *University of Washington*
David Hertzog, *University of Illinois*
Barbara Jacak, *Stony Brook University*
Robert Janssens, *Argonne*
Xiandong Ji, *University of Maryland*
Krishna Kumar, *University of Mass., Amherst*
Christoph Leemann, *Jefferson Lab*
Allison Lung, *Jefferson Lab*
Jay Marx, *Berkeley Lab*
Larry McLerran, *Brookhaven*
Curtis Meyer, *Carnegie-Mellon University*
Richard Milner, *MIT*
Joel Moss, *Los Alamos*
Al Mueller, *Columbia University*
Berndt Mueller, *Duke University*
Joe Natowitz, *Texas A&M University*
Witold Nazarewicz, *University of Tenn./ Oak Ridge*
Angela Olinto, *University of Chicago*
Shelley Page, *University of Manitoba*
Vijay Pandharipande, *University of Illinois*
Michael Ramsey-Musolf, *University of Connecticut*
Bob Redwine, *MIT*
Mark Riley, *Florida State University*
Hamish Robertson, *University of Washington*
Guy Savard, *Argonne*
Richard Seto, *UC Riverside*
Brad Sherrill, *Michigan State University*
Edward Shuryak, *Stony Brook University*
Michael Smith, *Oak Ridge*
Bob Tribble, *Texas A&M University*
Steve Vigdor, *Indiana University*
Henry Weller, *Duke University*
Michael Wiescher, *University of Notre Dame*
Bill Zajc, *Columbia University*

International Observers

Ken Imai, *Kyoto University*
Thomas Walcher, *Mainz*

Agency Representatives

Peter Rosen, *DOE*
Dennis Kovar, *DOE*
Jack Lightbody, *NSF*
Bradley Keister, *NSF*

Long-Range Plan Town Meetings

Sponsored by the American Physical Society
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NUCLEAR STRUCTURE AND ASTROPHYSICS

Oakland, California, November 9–12, 2000

Organizing Committee: Richard Casten, Yale Univ.; Joe Carlson, Los Alamos; Arthur Champagne, Univ. of North Carolina; Jolie Cizewski, Rutgers; Christopher Gould, North Carolina State Univ.; I-Yang Lee, Berkeley Lab; Kevin Lesko, Berkeley Lab; Joe Natowitz, Texas A&M Univ.; Witek Nazarewicz, Univ. of Tennessee/Oak Ridge; Stuart Pittel, Bartol Institute, Univ. of Delaware; Ernst Rehm, Argonne; Brad Sherrill, NSCL, Michigan State Univ.; Michael Wiescher, Univ. of Notre Dame (chair)

ASTROPHYSICS, NEUTRINOS, AND SYMMETRIES

Oakland, California, November 9–12, 2000

Organizing Committee: Baha Balantekin, Univ. of Wisconsin; Thomas Bowles, Los Alamos; John Doyle, Harvard Univ.; Christopher Gould, North Carolina State Univ.; Barry Holstein, Univ. of Massachusetts; Kevin Lesko, Berkeley Lab; Angela Olinto, Univ. of Chicago; Michael Ramsey-Musolf, Univ. of Connecticut/Jefferson Lab; Guy Savard, Argonne; Robert Tribble, Texas A&M Univ. (chair); Petr Vogel, Caltech; John Wilkerson, Univ. of Washington

ELECTROMAGNETIC AND HADRONIC PHYSICS

Thomas Jefferson National Accelerator Facility, December 1–4, 2000

Organizing Committee: Elizabeth Beise, Univ. of Maryland; Larry Cardman, Jefferson Lab; Charles Glashausser, Rutgers (chair); David Hertzog, Univ. of Illinois; Calvin Howell, Duke Univ.; Edward Hungerford, Univ. of Houston; Donald Isenhower, Abilene Christian Univ.; Harold Jackson, Argonne; Richard Milner, MIT-Bates; Joel Moss, Los Alamos; Al Mueller, Columbia Univ.; Fred Myhrer, Univ. of South Carolina; Peter Paul, SUNY Stony Brook; Brian Serot, IUCF; Dennis Skopik, Jefferson Lab (local chair); Werner Tornow, Duke Univ.

HIGH ENERGY NUCLEAR PHYSICS

Brookhaven National Laboratory, January 21–23, 2001

Organizing Committee: Gerry Garvey, Los Alamos; Victoria Greene, Vanderbilt Univ.; Barbara Jacak, SUNY Stony Brook; Thomas Ludlam, Brookhaven; Larry McLerran, Brookhaven; Berndt Mueller, Duke Univ.; Richard Seto, UC Riverside; Thomas Ulrich, Brookhaven; Steve Vigdor, Indiana Univ.; Xin-Nian Wang, Berkeley Lab; Glenn Young, Oak Ridge; William Zajc, Columbia Univ.

The white papers that emerged from these four meetings can be found at
http://www.sc.doe.gov/production/henp/np/nsac/lrp.html

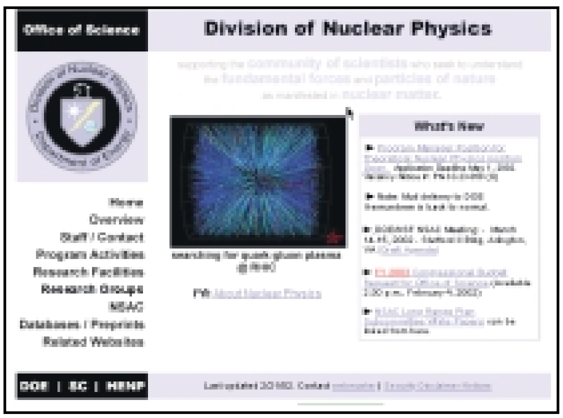
SCIENCE EDUCATION AND OUTREACH WHITE PAPER

B Balantekin, Univ. of Wisconsin; W Bauer, Michigan State; N Benczer-Koller, Rutgers; J.A. Cizewski, Rutgers; B. Clark, Ohio State; D. Haase, North Carolina State University; K. Kemper, Florida State; C. Mader, Hope College; R. McKeown, Caltech; M. McMahan, Berkeley Lab; J. Natowitz, Texas A&M; W. Rogers Westmont College.

Nuclear Science Web Sites

Good starting points for finding information on nuclear science in the U.S. are Web sites for the Department of Energy and the National Science Foundation:

http://www.sc.doe.gov/production/henp/np/index.html



http://www.nsf.gov/mps/divisions/phy/

Other organizations and major institutions and facilities, including those described in Chapter 3, also offer useful information:

American Chemical Society, Division of Nuclear Chemistry and Technology
http://www.cofc.edu/~nuclear/

American Physical Society, Division of Nuclear Physics
http://nucth.physics.wisc.edu/dnp/

Argonne National Laboratory, Physics Division
http://www.phy.anl.gov/

Bates Linear Accelerator Center,
Massachusetts Institute of Technology
http://mitbates.mit.edu/index2.stm

Brookhaven National Laboratory
http://www.bnl.gov/bnlweb/departments.html

E. O. Lawrence Berkeley National Laboratory
http://www.lbl.gov/

Indiana University Cyclotron Facility
http://www.iucf.indiana.edu/

Institute for Nuclear Theory,
University of Washington
http://int.phys.washington.edu/

Los Alamos National Laboratory
http://www.lanl.gov/worldview/

National Superconducting Cyclotron Laboratory,
Michigan State University
http://www.nscl.msu.edu/

Oak Ridge National Laboratory, Physics Division
http://www.ornl.gov/

Thomas Jefferson National Accelerator Facility
http://www.jlab.org/

A Glossary of Facilities and Institutions

Throughout this document, and especially in Chapter 2, major research facilities, research institutions, and universities are referred to by shorthand names, as listed below. Many abbreviated experiment and detector names have been omitted from this list.

AGS	Alternating Gradient Synchrotron (Brookhaven)
ATLAS	Argonne Tandem-Linac Accelerator System
CEBAF	Continuous Electron Beam Accelerator Facility (Jefferson Lab)
CERN	European Organization for Nuclear Research (Switzerland)
COSY	Cooler Synchrotron (Germany)
DESY	Deutsches Elektronen-Synchrotron (Germany)
EIC	Electron-Ion Collider
GSI	Gesellschaft für Schwerionenforschung (Germany)
HRIBF	Holifield Radioactive Ion Beam Facility (Oak Ridge)
ILL	Institut Laue-Langevin (France)
ISAC	Isotope Separator and Accelerator (TRIUMF)
IUCF	Indiana University Cyclotron Facility
JHF	Japanese Hadron Facility
JINR	Joint Institute for Nuclear Research (Russia)
LAMPF	Los Alamos Meson Physics Facility (now LANSCE)
LANSCE	Los Alamos Neutron Science Center
LENA	Laboratory for Experimental Nuclear Astrophysics (TUNL)
LHC	Large Hadron Collider (CERN)
MIT-Bates	Bates Linear Accelerator Center (MIT)
NERSC	National Energy Research Scientific Computing Center (Berkeley Lab)
NIST	National Institute of Standards and Technology
NSCL	National Superconducting Cyclotron Laboratory (Michigan State)
NSL	Nuclear Science Laboratory (Notre Dame)
NUSL	National Underground Science Laboratory
ORELA	Oak Ridge Electron Linear Accelerator
ORLaND	Oak Ridge Laboratory for Neutrino Detectors
PSI	Paul Scherrer Institut (Switzerland)
RCNP	Research Center for Nuclear Physics (Japan)
RHIC	Relativistic Heavy Ion Collider (Brookhaven)
RIA	Radioactive Ion Accelerator
RIKEN	The Institute of Physical and Chemical Research (Japan)
SLAC	Stanford Linear Accelerator Center
SNO	Sudbury Neutrino Observatory (Canada)
SNS	Spallation Neutron Source (Oak Ridge)
SPS	Super Proton Synchrotron (CERN)
TRIUMF	Tri-University Meson Facility (Canada)
TUNL	Triangle Universities Nuclear Laboratory (Duke)

Argonne National Laboratory

Ball State University (Indiana)

E. O. Lawrence Berkeley National Laboratory **(Berkeley Lab)**

Brookhaven National Laboratory

California State University at Northridge

California Institute of Technology **(Caltech)**

College of **William and Mary**

Duke University

Fermi National Accelerator Laboratory **(Fermilab)**

Florida State University

Hope College (Michigan)

Thomas Jefferson National Accelerator Facility **(Jefferson Lab)**

Lawrence **Livermore** National Laboratory

Los Alamos National Laboratory

Johannes Gutenberg University, **Mainz** (Germany)

Massachusetts Institute of Technology **(MIT)**

Michigan State University

University of **Notre Dame**

Oak Ridge National Laboratory

Rutgers, The State University of New Jersey

Sandia National Laboratories

San Jose State University (California)

Stony Brook University **(SUNY Stony Brook)**

Texas A&M University

University of California, Berkeley **(UC Berkeley)**

University of California, Irvine **(UC Irvine)**

University of California, San Francisco **(UC San Francisco)**

University of Washington

Yale University