



**OVERVIEW OF  
OPPORTUNITIES IN NUCLEAR SCIENCE**

A Long-Range Plan for the Next Decade

June 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 Physics Program

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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.

This Plan has emerged from a process in which more than a thousand members of the nuclear science community participated. 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.

This document is a condensed version of the full long-range plan. It contains an overview of the opportunities open to the field, and a summary of our recommendations. Copies of the full plan may be obtained from

**Division of Nuclear Physics, SC-23**

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**Germantown, Maryland 20874-1290**

## On the cover:

### **First Events from RHIC**

With the Relativistic Heavy Ion Collider (RHIC), the field's newest accelerator, nuclear physicists are now hunting for a new state of matter which is believed to have occurred during the first millionth of a second of the universe's existence: the quark-gluon plasma. Here is an example of a collision between two gold nuclei as seen by the STAR detector at RHIC. Shown is a view of the tracks left behind by the particles produced in a collision that occurred at the center.

## Nuclear Science Today

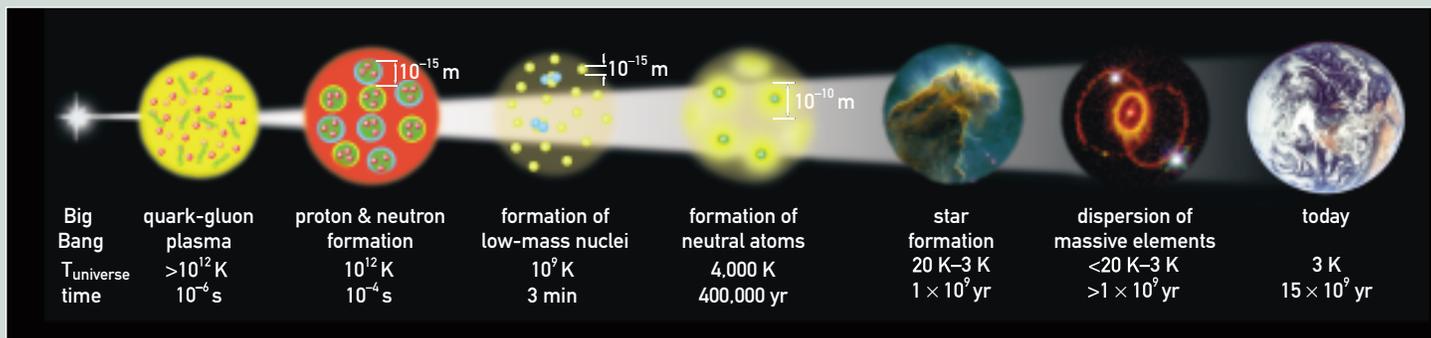
Nuclear science is a key component of the nation’s research portfolio, providing fundamental insights into the nature of matter and nurturing applications critical to the nation’s health, security, and economic vitality. It is a field with tremendous breadth that has direct relevance to understanding the evolution of matter in the universe.

During the 20th century, nuclear science began by studying the structure and properties of atomic nuclei as assemblages of protons and neutrons which interact through three of the four fundamental forces of nature: primarily the strong, electromagnetic and weak forces. Research focused on nuclear reactions, the nature of radioactivity, and the synthesis of new isotopes and new elements heavier than uranium. Great benefit to society emerged from these pioneering efforts, especially in medicine. But today, at the dawn of a new century, nuclear science is much more than this. The protons and neutrons themselves have a complex structure: they are composed of quarks and gluons that seem forever trapped inside them—physicists talk about the quarks and gluons being “confined”. The description of the interaction among the quarks has given rise to a new

theory, quantum chromodynamics (QCD). 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 foundation for understanding nuclear phenomena and is now central to much of contemporary nuclear research. Modern studies of the structure of exotic nuclei play a vital role in developing our understanding 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. In addition, atomic nuclei have proven to be unique laboratories where our description of the fundamental laws of nature can be tested with exquisite precision.

The broad scope of contemporary nuclear science intersects with that of several other scientific disciplines. For example, high-energy physics, nuclear physics and astrophysics are now closely linked in efforts to understand the immediate aftermath of the Big Bang. Strong parallels also exist between the structure of complex nuclei and the nanostructures of interest in the emerging fields of nanoscience and nanotechnology. The impact of the field can be seen not only in basic science, but also in nuclear medicine, nuclear power, homeland security programs, and numerous other practical applications, from smoke detectors to scanners for explosives.

### The Nuclear Physics of the Universe

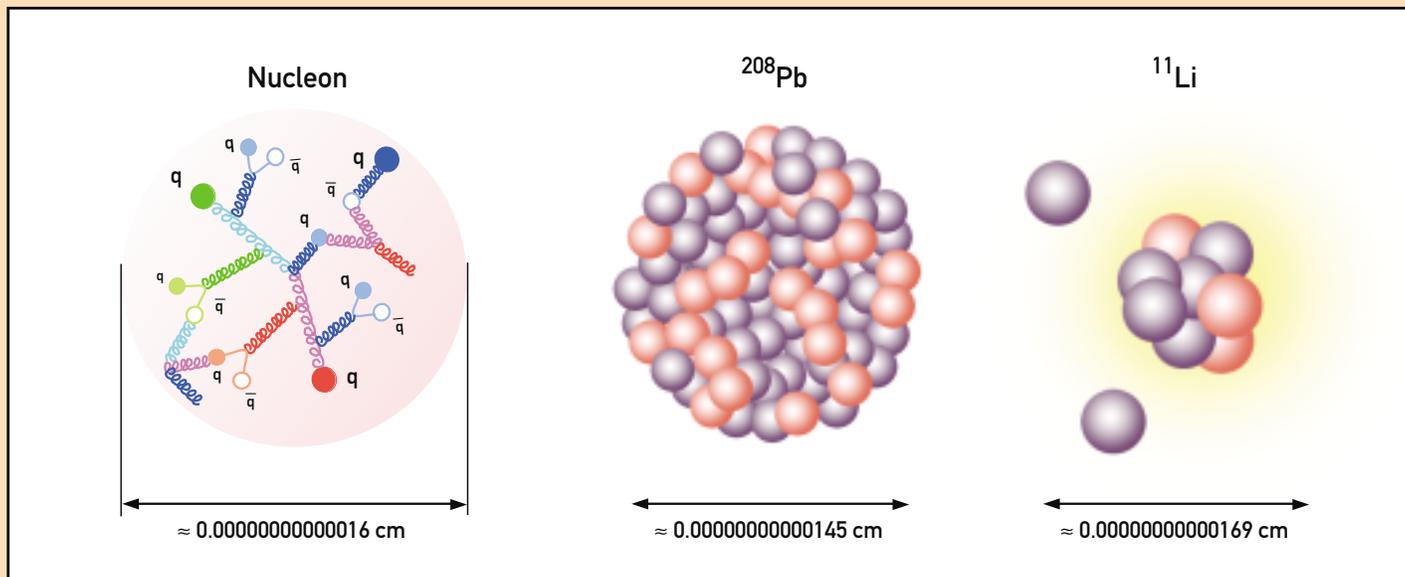


This figure illustrates stages in the evolution of the universe where nuclear physics has played a central role. Of particular current interest are the transition from the quark-gluon plasma to protons and neutrons, which took place in the first few microseconds after the Big Bang, and the synthesis of nuclei which is still occurring today. Gravity causes clouds of atoms to contract into stars, where hydrogen and helium fuse into more massive chemical elements

through nuclear reactions. Once their nuclear fuel is exhausted, many stars collapse and then explode as supernovae. These are cataclysmic events in which the most massive elements are formed and dispersed into space to be incorporated into newly forming stars.

(Graphic – Copyright 1998 Contemporary Physics Education Project.)

## Nucleons and Nuclei



Contemporary nuclear physics studies the structure of both the nucleon (the proton or the neutron) and the nucleus. On the left is a pictorial representation of the substructure of the nucleon according to the theory of quantum chromodynamics (QCD). Trapped inside the nucleon are three point-like quarks (heavy colored dots) which interact by exchanging gluons (spring-like lines). The strong interactions induce additional gluons and a “sea” of virtual quark ( $q$ )-antiquark ( $\bar{q}$ ) pairs (smaller, fainter dots). The colors of the constituents represent their intrinsic strong charges, the source of their participation in QCD interactions. In the nucleon, the quarks only appear in groups of three or in quark-antiquark pairs. The nature of the strong interactions inside the nucleon and the relative contributions of various types of quarks and gluons to the nucleon’s properties are major topics of contemporary research.

Nuclei are collections of the two types of nucleons. In the middle is a representation of  $^{208}\text{Pb}$  (lead-208) with 82 protons (in red) and 126 neutrons (blue dots). Crucial questions concern which combinations of protons and neutrons can form a nucleus, and how the properties of nuclei evolve with changes in the proportions of the number of protons and neutrons. Surprises abound in first studies of “exotic” nuclei, such as  $^{11}\text{Li}$  (lithium 11), a nucleus with an unusually large number of neutrons—there are eight for only three protons. In  $^{208}\text{Pb}$ , protons and neutrons assemble in a close packed, spherical arrangement. The structure of  $^{11}\text{Li}$  is quite different with three protons and six neutrons forming a tight core and the two remaining neutrons spreading throughout a volume whose size is as large as that occupied by the far heavier  $^{208}\text{Pb}$ . Except for the lightest systems, virtually nothing is known about nuclei far from stability on the neutron-rich side.

Even though one cannot anticipate the answers in basic research, the return on the public’s investment can be maximized through long-range planning of the most promising avenues to explore and the resources needed to explore them. This document is a summary of the 2002 Long Range Plan for Nuclear Science, which was developed by the Nuclear Science Advisory Committee over the past year at the request of the Department of Energy (DOE) and the National Science Foundation (NSF). The full report can be found on the DOE Nuclear Physics Website.

## The Scientific Agenda

Today, nuclear science can be broadly characterized by five scientific questions that define the main lines of inquiry.

**What is the structure of the nucleon?** Protons and neutrons are the building blocks of nuclei, 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 challenges of modern science.

**What is the structure of nucleonic matter?** The coming decade will focus especially on the properties of exotic nuclei, i.e. of nuclei with ratios of protons to neutrons very different from those that exist in the stable nuclei of the world around us. We expect to find new phenomena and new structure unlike anything known. In doing so, we hope to uncover important facets of the nuclear force that cannot be observed in stable systems, with the ultimate goal to provide a quantitative description of all nuclei within a single theoretical framework.

**What are the properties of hot nuclear matter?** The quarks and gluons that compose each proton and neutron are normally confined within these nucleons. However, QCD predicts that, if an entire nucleus is heated sufficiently, individual nucleons will lose their identities, and 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 which is believed to have been the state of all matter during the first millionth of a second of the universe’s existence.

**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 radiation; the mechanism responsible for the collapse and explosion of stars (supernovae); the search for the origin of galactic and extragalactic gamma-ray sources—involve fundamental nuclear physics issues that must be studied in the laboratory. The partnership between nuclear physics and astrophysics will become ever more crucial in the coming decade, as data from

astronomy’s powerful new telescopes and orbiting observatories extend our knowledge of the cosmos.

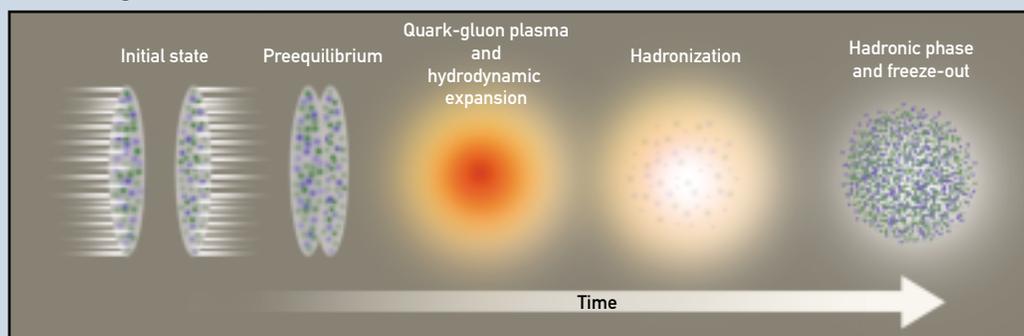
**What is to be the new Standard Model?** Recent experiments at the Sudbury Neutrino Observatory (SNO) and with the SuperKamiokande detector, described in the section below, have provided the long-sought demonstration that our current Standard Model of particle physics is incomplete. This opens up possibilities for exciting discoveries in the next decade. Precision experiments by nuclear physicists, especially in a background free environment deep underground, 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 the nucleons.** A new generation of experiments, combined with new sophisticated theoretical and computational techniques, has challenged earlier descriptions of the structure of the proton and the neutron. Through a number of experiments, we have come to realize that quark spins alone account for only a fraction of the nucleon’s overall spin. A new high-resolution spatial map of the proton

### 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 colliding gold nuclei give rise to thousands of 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.

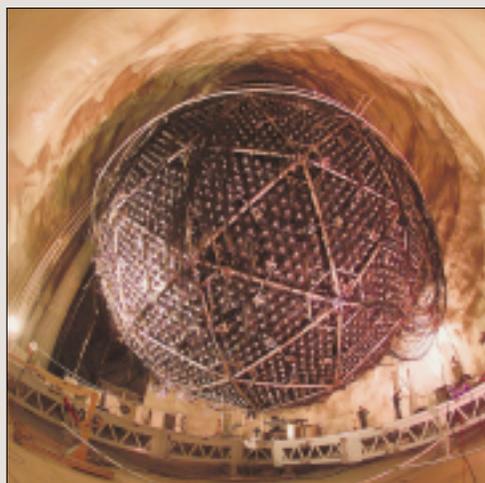
points to an unexpected depletion of charge near its center, not yet explained by current models. Surprisingly, the traditional description of nuclear forces continues to account well for the way charge is distributed in the deuteron, the nucleus made out of the assembly of a proton and a neutron, even at distances where the internal structures of these two nucleons overlap strongly.

**Challenging traditional descriptions of the atomic nucleus.** Pioneering studies of exotic nuclei with unusual numbers of protons and neutrons 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 the heaviest elements (the superheavy elements) goes through nuclei with deformed shapes. Striking evidence for phase transitional behavior (in finite nuclei) has emerged from studies of nuclear shapes and in nuclei excited to high temperatures. Recent 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.

**The search for matter at extremely high energy density.** During the first year of operations at RHIC, measurements of the number and energies of particles produced in collisions between gold nuclei moving at nearly the speed of light have shown that matter was produced at temperatures and densities more than 20 times that of atomic nuclei. Under such extreme conditions matter is believed to be in a new state—the quark-gluon plasma. The rate of fast moving particles emitted in these collisions was found to be considerably smaller than that seen in comparable collisions between protons—an effect occurring only if the interactions among the produced particles are very strong. These results provide an outstanding confirmation of the picture that originally motivated the field of ultrarelativistic nuclear collisions.

**The origin of the elements and the evolution of stars.** Long-term multidisciplinary efforts to understand how our Sun works and how the lightest nuclei came into existence in the early universe (following the Big Bang) have now been validated. Important advances have also occurred in our understanding of the nuclear reactions that govern stellar evolution. Nuclear measurements on short-lived nuclei and a new generation of computational techniques have brought us closer to the identification of the cosmic sites where the heavy elements which make up most of our world are being produced.

### Counting nature's phantoms



Neutrinos are particles like electrons, but with no charge and very little mass: this makes them difficult to detect despite the fact that large numbers of neutrinos are produced in the Sun. The SNO neutrino detector, shown here before it was filled with water, is located 2000 m underground at the Creighton mine in Sudbury, 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 (deuterium oxide) water. Together with results from another underground detector, Super-Kamiokande located in Japan, SNO has provided conclusive evidence that neutrinos change their character on their journey from the solar core to the Earth.

**Tracing the missing mass of the universe.** Observations of the neutrinos (particles like electrons, but with no charge) 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 remarkable new measurements (at the Sudbury Neutrino Observatory (SNO) and at the SuperKamiokande detector) showed that the neutrinos change their character on their 93-million-mile journey from the solar core to the Earth; such a transformation requires 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. We now also know that this additional mass is insufficient to stop the expansion of the universe.

## Impact and Applications of Nuclear Science

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 to meet 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.

One of every three hospitalized patients in the U.S. today undergoes a nuclear medicine procedure. Three areas of particular significance are the use of radioisotopes, diagnostic imaging, and cancer radiation therapy. These techniques 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 these areas. 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 depend on the technologies of nuclear science such as proton radiography and activation analysis.

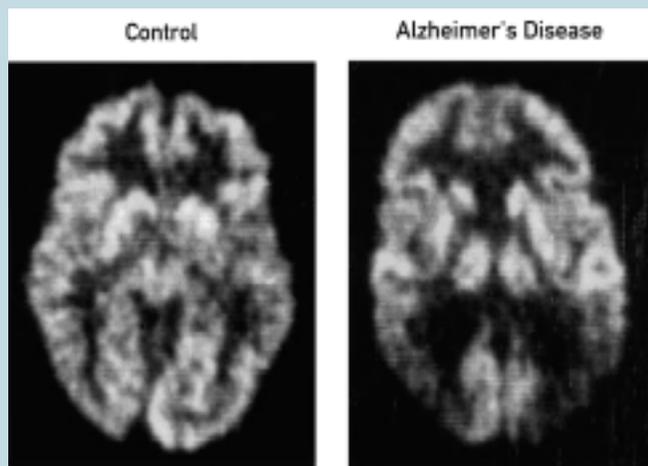
Nuclear energy is an important component of the nation's national energy policy. In this area, advanced nuclear fuel cycles and next-generation technologies offer great promise in resolving societal questions regarding safety through resistance against increased proliferation and reduced waste streams.

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 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. These techniques also have great impact in archaeology, artifact dating, art authentication, and the exploration of Mars and the Moon.

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 manufacturing, 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.

Many of these applications were discussed in considerable detail 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.



### Slice of life: nuclear science at work for society

Positron emission tomography (PET) provides insights unavailable with most imaging techniques. Here, a glucose labeled with radioactive  $^{18}\text{F}$  is used as a tracer of brain functions, and PET highlights the difference between a normal brain and a brain affected by Alzheimer's disease.

## 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 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.



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

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.



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.

## 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,



Dr. Nancy Stoyer, examining an actinide sample in a glove box 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.



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

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

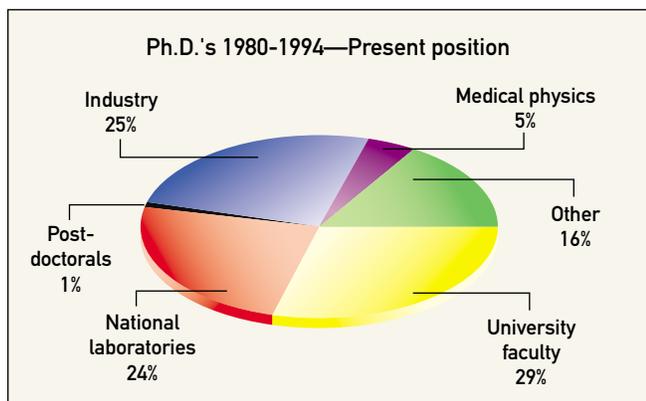
12 clients and manages 63 portfolios with a total value in excess of \$4 billion. Zecher and Handzy feel that their "training as physicists, the analytic skills and the skills to manage large amounts of data that come from working at a major experimental facility, has been one of the cornerstones of our success."

## Nuclear Science in the National Interest

A 1999 survey of nuclear science by the National Research Council, *Nuclear Physics: 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 tools 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

### Career Choices



The pie chart shows the current positions of nuclear science Ph.D. recipients for the period 1980—1994. The results are based on a survey of 19 major universities offering this degree.

### Outreach



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.

at the defense laboratories. Indeed, about 20% of recent Ph.D.'s 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.

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.

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, many experimental facilities are now located at national laboratories. However, successive long-range plans have emphasized the importance of continuing to provide adequate support for 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 University, 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 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.

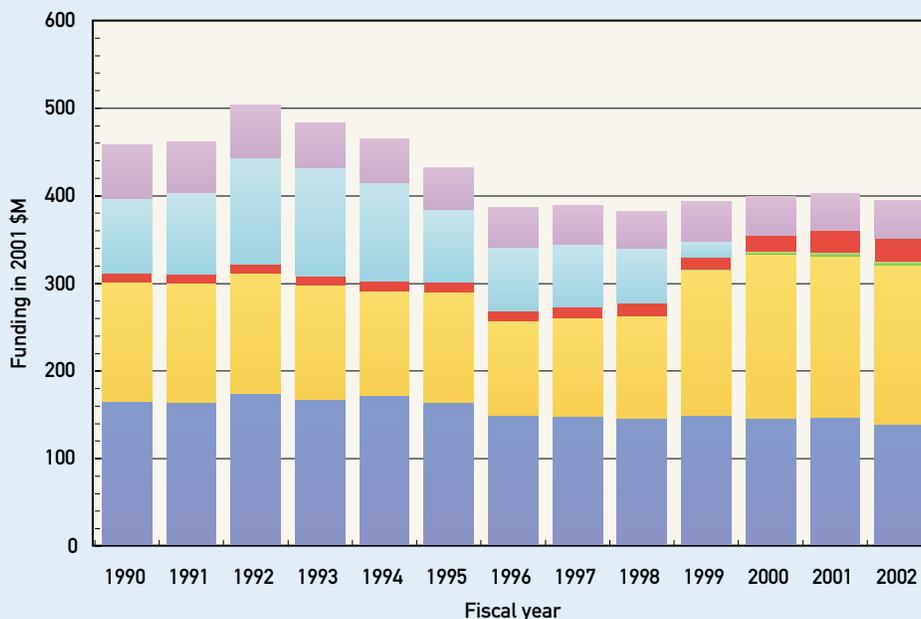
Specifically, it is imperative to

- 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.

Since 1991, several new facilities for nuclear science research have come on-line, including the CEBAF electron accelerator at the Jefferson Laboratory, the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory and the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory (NSCL) on the campus of Michigan State University. 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. With these investments, U.S. scientists are poised to make significant advances in answering many of the important scientific questions outlined in this report. However, as shown in the graph below, funding for nuclear science has decreased by about 25% during the same period, when inflation is taken into account. This has led to a situation where our ability to exploit these opportunities is threatened and an increase in operating funds would provide exceptional benefit.

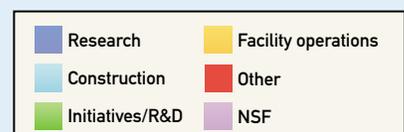
The research of approximately 2000 U.S. scientists, including 500 students and postdoctoral fellows is tied to the operation of the national user facilities. Unfortunately, in the past year alone, these facilities ran at 15–45% below their optimal levels. The recommended increase in operating funds would eliminate this shortfall and produce a dramatic increase in scientific productivity through increased operating hours, improved reliability, and an enhanced ability to upgrade experimental equipment.

The increase in funding would also be used to invigorate the university-based research groups that contribute strongly to the intellectual and technical development of



**Funding for nuclear science, 1991–2000**

The chart shows total DOE and NSF funding in fiscal 2001 dollars. All categories except "NSF" reflect DOE funding only.



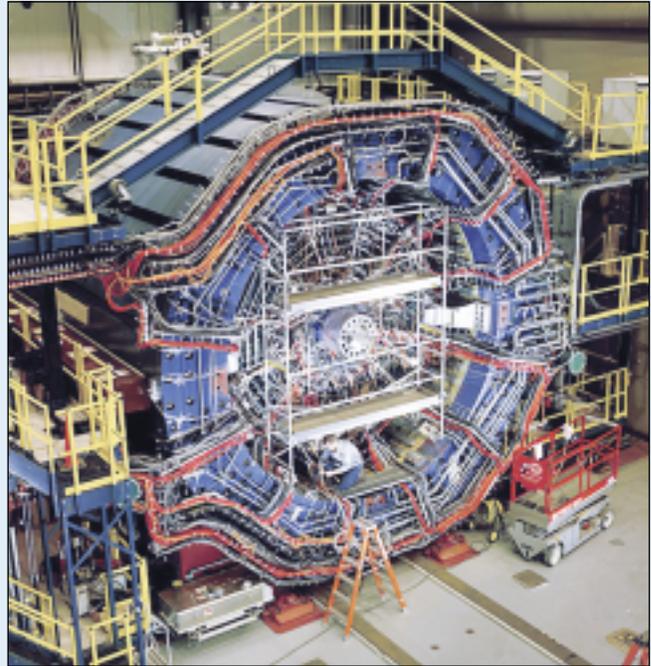


#### **Reflections of the next generation**

The Large Area Silicon Strip Array (LASSA) at the NSCL reflects the images of several graduate and undergraduate students who were involved in its design and construction.

nuclear science. 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. 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.

Finally, the increase would be used to significantly strengthen theoretical research, which has been particularly hard hit in recent years. It currently accounts for less than 5% of total funding for nuclear science, in contrast to the 10% recommended in past long-range plans. Experimentalists consistently emphasize the crucial role



#### **One of Nuclear Science's newest detectors**

The STAR detector at RHIC characterizes particles produced in collisions between two nuclei moving at speeds close to the speed of light.

of theory research: it motivates and guides experimental activities, and it synthesizes knowledge gained from experiments into new and more general conceptual frameworks. In addition, the nature of this work is changing as very large scale computing increases in importance. A number of mechanisms are proposed in the Long Range Plan to identify the areas of greatest promise and to attract and retain young theorists of the highest caliber.

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

## 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.

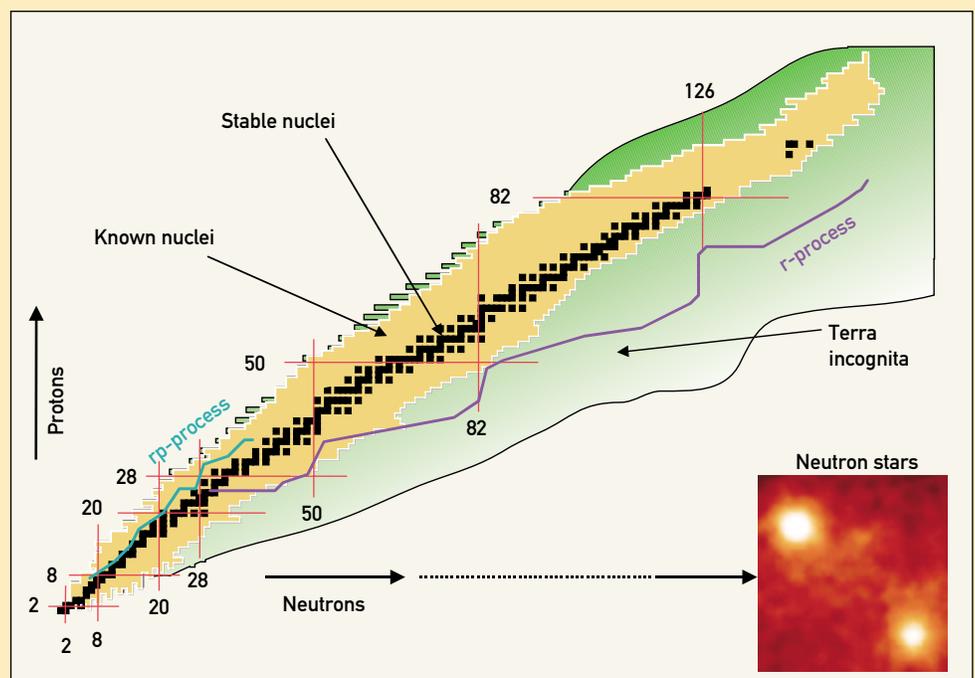
One of the principal challenges of nuclear science is to understand how nuclei are constructed from their constituent parts. However, until recently we have lacked an important experimental tool needed to answer this challenge, that is the ability to vary the proportions of the two main components of a nucleus—neutrons and protons—over a wide range, far from the configurations of stable nuclei. In doing so, we hope to uncover important facets of the nuclear force that cannot be observed in stable systems. The technology of high-intensity heavy-ion accelerators

and new 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. In response to these new opportunities, the nuclear science community has proposed the Rare Isotope Accelerator (RIA) project, a bold new concept in exotic-beam facilities.

The nuclear landscape (figure below) defines the territory of RIA research. Most of what we know about nuclei today comes from studies with stable nuclei: these are the black squares on the figure. By adding either protons or neutrons to one of these stable nuclei, one moves away from the “line of stability”, first producing unstable nuclei and finally reaching the drip lines where nuclear binding forces are no longer strong enough to hold nuclei together. The yellow squares indicate unstable nuclei that have been produced and studied in the laboratory. But many thousands of radioactive nuclei have yet to be explored: this nuclear *terra incognita* is indicated in green. RIA will expand our investigations into the nature of nucleonic matter by providing experimental access to these nuclei. It will define and map the limits of nuclear existence and allow us to explore the structure of the exotic systems that inhabit these boundaries. For example, it will be possible to investigate whether nuclei with a large excess of neutrons develop a neutron “skin”, that is a region of almost pure neutron matter. If so, questions about regarding the density of particles in this region and its spatial extent. On the nuclear landscape, the red

### The territory of RIA research

On this chart of the nuclides, black squares represent stable nuclei and the yellow squares indicate unstable nuclei that have been produced and studied in the laboratory. The many thousands of these unstable nuclei yet to be explored are indicated in green (Terra incognita). The red vertical and horizontal lines show the magic numbers, reflecting regions where nuclei are expected to be more tightly bound and have longer half-lives. The anticipated paths of astrophysical processes for nucleosynthesis (r-process, purple line; rp-process, turquoise line) are also shown.



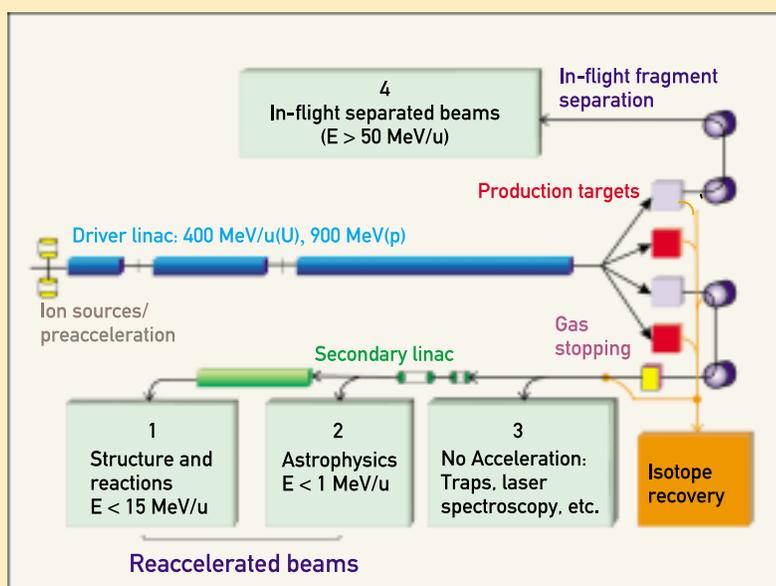
vertical and horizontal lines show the “magic numbers”, reflecting specific combinations of protons and neutrons that are particularly stable. The occurrence of magic numbers has been inferred mostly from stable nuclei, and forms the basis for the nuclear shell model, a hallmark of our understanding for half a century. Whether these magic numbers change or even persist in the terra incognita is an issue of much debate and relates to our present lack of understanding of the nature of the strong force that binds together a collection of protons and neutrons to form a nucleus.

While we have hitherto been unable to produce most unstable nuclei in the laboratory, Nature has never experienced such limitations: short lived, exotic nuclei have been—and continue to be—made in cataclysmic stellar events such as supernovae. On the nuclear landscape (see page 12), the anticipated paths of astrophysical processes for the formation of the heaviest elements (r-process, purple line; rp-process, turquoise line) are also shown. RIA will stimulate our quest to understand the origin of the elements and the generation of energy in stars by providing experimental access to the nuclei along these astrophysical pathways. This second theme addresses nothing less than questions about our own origins. RIA will provide key data, such as masses, lifetimes, and reaction rates, needed for a quantitative understanding of the important nucleosynthesis processes by which most of the material around us was produced. Finally, RIA will provide us with opportunities to test fundamental

conservation laws. Its unique capabilities, including the ability to create large quantities of specific exotic nuclei which can then be trapped, will permit sensitive tests of basic laws of nature, of basic symmetries and other important aspects of, in particular, the weak interaction (one of the four fundamental forces, together with gravitational strong, and electromagnetic interactions).

In addition to its basic research agenda, RIA will provide important capabilities in number of applied areas including medicine and national security. For medicine, RIA’s high intensity beams and isotope separation capabilities will provide opportunities to generate a wide variety of isotopes not currently available. This will lead to the development of materials best suited for diagnostic and therapeutic procedures. Another application in the health area is the use of implanted species for studying the wear of artificial joints. In the national security arena, RIA will provide significant new capabilities for the Science-Based Stockpile Stewardship (SBBS) program by its ability to measure important reactions involving unstable nuclei. RIA will also provide important information needed to determine the most effective means to transform nuclear waste.

A schematic of the RIA facility is shown below. The key to the scientific discovery potential of the facility is its ability to provide the highest-intensity beams of stable heavy ions for the production of rare isotopes. This concept builds on developments in superconducting technology in the U.S. and Europe over the past two decades.



### Schematic of the RIA facility

The heart of the facility is composed of a driver accelerator capable of accelerating every element of the periodic table up to at least 400 MeV/nucleon. Rare isotopes will be produced in a number of dedicated production targets. Upon extraction from the targets, these 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. Isotopes will also be harvested for applications (Isotope recovery). Fast beams of rare isotopes can also be used directly after separation in a high-resolution fragment separator (Area 4). RIA brings together the most powerful known techniques for rare isotope production in a single facility.

## 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 a major intellectual revolution: the foundation for the new Standard Model is being laid at the same time that some of the deepest secrets of the cosmos are being revealed. This revolution has been stimulated by recent results on neutrinos, some of the most elusive particles in Nature. Neutrinos belong to the same family of particles as electrons, but they have no charge. Until recently, scientists thought that the three known types of neutrinos also had no mass. However, remarkable recent measurements show that the different kinds of neutrinos can change into one another as they fly through space. This transformation can only take place if they have mass, generating both new questions for theory, since the Standard Model of particle physics provides no mechanism for it, and targeted goals for new experiments. The data available today yield mass differences, but what are the actual masses? Is the neutrino different from its antiparticle, the antineutrino? Are there "sterile" neutrinos that is, neutrinos that react much more weakly with detectors than the three known neutrino types? The National Underground Science Laboratory (NUSL) will offer opportunities to answer some of these questions by enabling a new generation of experiments with much improved detection sensitivity.

The NUSL will also contribute in a major way to answering questions in astrophysics. Violent stellar explosions (supernovae) are thought to be the result of runaway nuclear reactions that sometimes occur when matter is compressed under the pull of a star's gravity. How does this process work and culminate in an explosion? What role do neutrinos play? Can we extract information from the neutrino flux on the nature of the dense nuclear matter in stellar 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 some 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 accelerator for experiments underground will address a number of fundamental questions, and will be complementary to data gathered with RIA. Do we understand the nuclear 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?

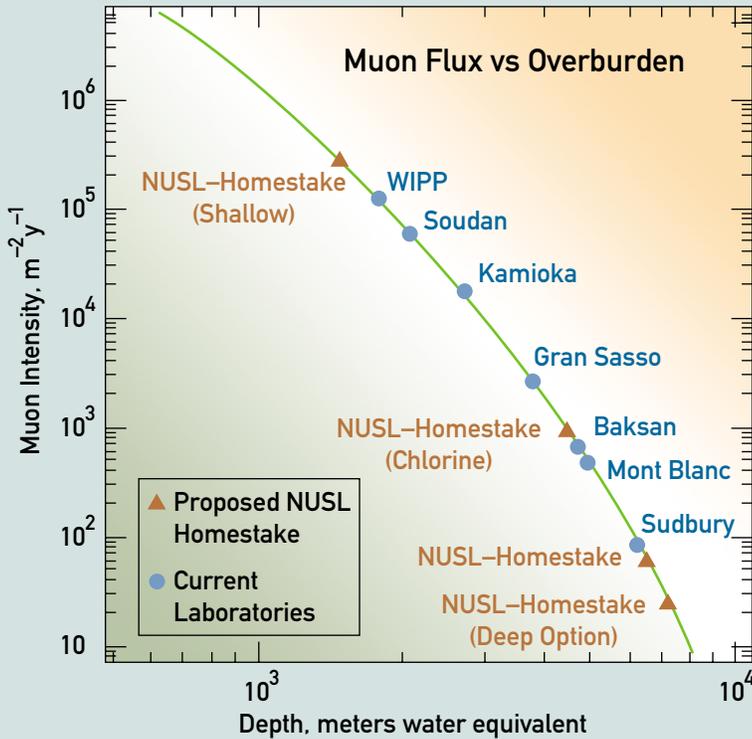
The NUSL will also address a wider science program, including geology and microbiology, as well as applications in industry and national defense. Many next-generation experiments in these fields must be substantially more sensitive than current ones and thus require shielding that can only be provided by working at great depth underground.

The remaining question is: why a new underground laboratory in the U.S.? The underground laboratories in Europe and Japan (see figure on opposite page) 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 mine houses the SuperKamiokande detector, an effort that has produced profoundly influential solar and atmospheric neutrino discoveries. Both of these laboratories are fully subscribed,

and several current experiments have thus sought space in less ideal underground environments. More important, however, is the depth of these laboratories: Kamiokande is at 2700 meters water equivalent (mwe), 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.

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 ultra-sensitive neutrino experiments, the U.S. nuclear physics community is committed to developing the NUSL. This facility will host international collaborations and will become the preeminent center in the world for doing underground science. The Homestake mine in South Dakota offers an ideal location for NUSL, with available experimental sites between 2100 and 7200 mwe below the surface (see figure below). A second potential site, at San Jacinto in California, has also been identified.



### Going deep underground

The reduction in the flux of muons, particles like electrons but with a larger mass, is representative of the impressive reduction in background due to cosmic rays that can be achieved by going deeper and deeper underground. The curve shows the location of current laboratories in Japan (Kamioka), Europe (Baksan, Mont Blanc, Gran Sasso) and in North America (Soudan, Sudbury, WIPP) together with the various depths where laboratories could be installed at the proposed National Underground Science Laboratory (NUSL) in the Homestake mine near Lead (South Dakota). 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 description of matter, and the nature of quark confinement.

Almost two decades have passed since the parameters of the CEBAF electron accelerator at the Jefferson Laboratory were defined. During this period, our understanding of strongly interacting matter has evolved considerably, posing new questions best addressed by a CEBAF-quality accelerator that can operate 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.

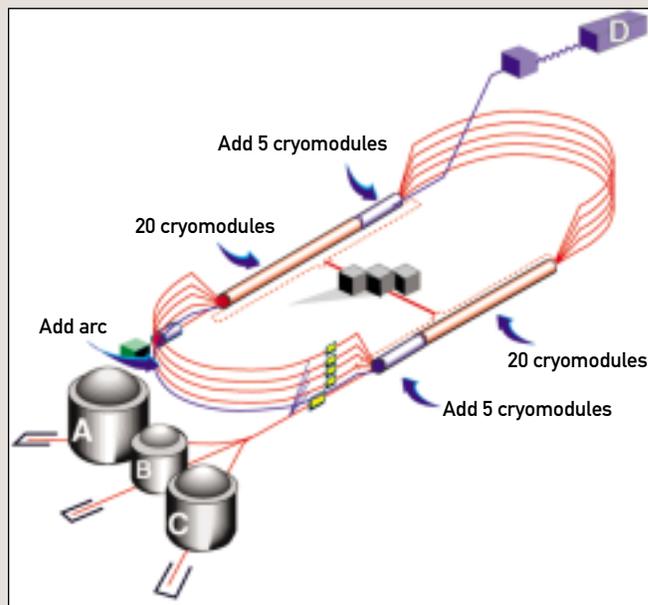
The 12 GeV beam energy will provide an exceptional opportunity to study a family of new particles, called “exotic mesons”, long predicted by quantum chromodynamics, but whose existence has only recently been hinted at experimentally. These particles are important because their properties should provide crucial insight into the mechanism responsible for the confinement of quarks inside the nucleon (see the figure on page 4 for more information). Definitive experiments to map out these properties require the energy upgrade and a suite of detectors to be housed in a new experimental area.

The higher the beam energy, the more precisely the electron can “sense” the individual quarks and gluons that make up a nucleon. In other words, the higher the beam energy, the smaller the distance scale that the electron can probe: electrons are no longer scattered off a proton or a neutron, but rather off one of their constituents.

This opens the door to the full exploration of the regime where scattering from the three basic (so-called “valence”) quarks inside the proton and the neutron dominates, and will clarify our understanding of the structure of these two nucleons.

The success of the original CEBAF design is one of the key factors that make a cost-effective upgrade possible. In the original design electrons reach a maximum energy of 4 GeV by passing five times through two straight accelerating sections (see figure below). The two linear accelerators (linacs) are linked by recirculation arcs where magnets bend the particles and keep them on the proper trajectory. These linacs have exceeded their design goal and CEBAF is currently running at a 6 GeV maximum energy. New accelerator structures have recently been tested. They demonstrate that a further increase of the beam energy to 12 GeV is now within reach. 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.

### Moving up to 12 GeV



The four main upgrades to the CEBAF accelerator at the Jefferson laboratory required to double the energy of the electron beam from 6 to 12 GeV are indicated on the schematic drawing of the facility together with the proposed new experimental area, hall D.

## Other initiatives

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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. The first two initiatives, in particular, are in this category and require ongoing R&D.

**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 (i.e., the intensity of the colliding beams) 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.

For the field to be ready to implement these initiatives, 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.

**$4\pi$  Gamma-Ray Tracking Array.** The detection of gamma-ray emissions from excited nuclei plays a vital role in nuclear science: this has been proven time and time again by the success of Gamma-sphere, the national gamma-ray facility in operation since the early nineties. The physics justification for a  $4\pi$  tracking array 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 accelerators, including stable- and radioactive-beam facilities, as well as RIA.

**Neutron Initiative.** Intense beams of pulsed cold neutrons (i.e., neutrons of low energy) and ultracold neutron sources (UCNs) offer sensitive tools for testing fundamental symmetries of nature and for elucidating the structure of weak interactions. Experiments are now under way with pulsed cold neutrons at LANSCE at Los Alamos National Laboratory, and in the future, we expect to take similar advantage of the Spallation Neutron Source (SNS), now under construction at Oak Ridge National Laboratory. 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 the 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 National Laboratory 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 the 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

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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.** A funding profile for the implementation of the recommendations of this long-range plan is given in the figure on the next page. 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.

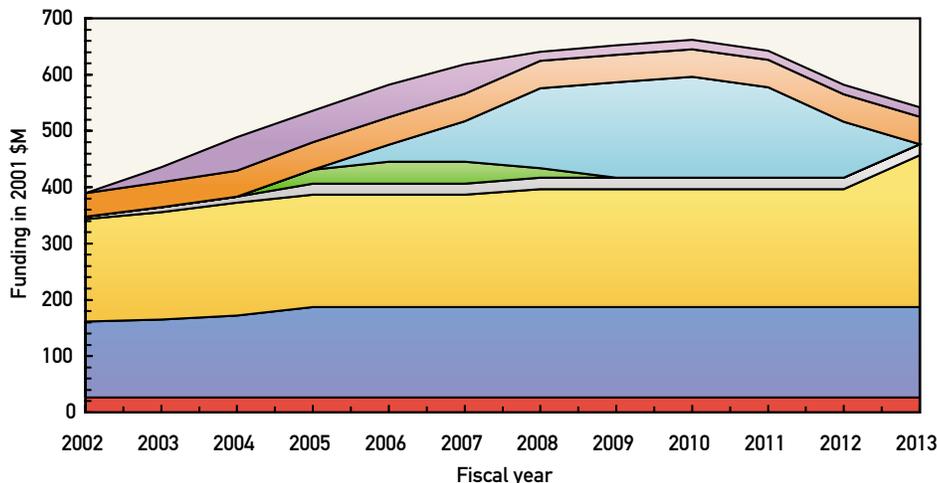
**Recommendation 2 - Rare Isotope Accelerator.** RIA is our highest priority for major new construction. It will allow us to realize the outstanding scientific opportunities offered by research with rare isotopes and to ensure continued U.S. leadership in nuclear structure and nuclear astrophysics research. 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



**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. This includes the 15% increase discussed in Recommendation 1.

could not be found from 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 for the next generation of underground experiments.

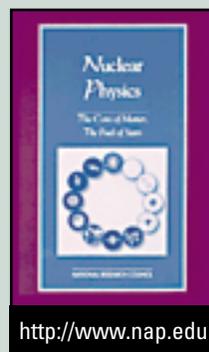
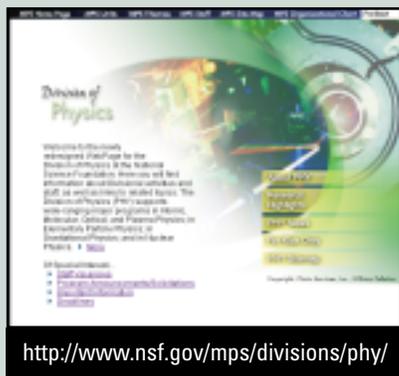
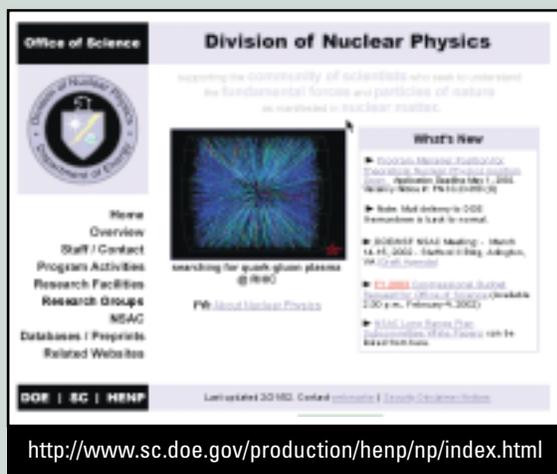
We should emphasize that smaller initiatives—even medium-sized initiatives such as the Jefferson Lab Upgrade—should be accommodated within a constant-effort budget. However, in such a scenario, the current breadth of the program could not be sustained. To maintain world leadership in a few core areas of the field, difficult choices would have to be made. 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.

The value of the NSAC Long Range Plan process both to the nuclear science community and to the supporting agencies and Congress has been demonstrated repeatedly over many years. It has provided the framework for consensus on major initiatives and for difficult priority choices. It has provided guidance on the commitment of financial resources and scientific manpower. This Long Range Plan renews the process of responsibly shaping the nation’s investment in nuclear science through a partnership between the research community and the public. The return on that investment is outstanding nuclear science, and word leadership for the U.S. in this field.

# 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:



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://nuclth.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.nsl.msu.edu/>

Oak Ridge National Laboratory, Physics Division  
<http://www.ornl.gov/>

Thomas Jefferson National Accelerator Facility  
<http://www.jlab.org/>

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