NUCLEAR SCIENCE IN DOE: ASSESSMENT AND PROMISE

A REPORT OF THE DOE/NSF NUCLEAR SCIENCE ADVISORY COMMITTEE
(NSAC)

May 1994

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I. EXECUTIVE SUMMARY

In February 1994 the Nuclear Science Advisory Committee (NSAC) to the Department of Energy (DOE) and the National Science Foundation (NSF) was charged by the agencies to update its planning advice for the DOE Nuclear Physics program. The program is to be "assessed against scientific priorities contained within existing recommendations," and "needs and priorities should be discussed within the framework of the Long Range Plan and subsequent NSAC reports" (Appendix 1). This charge must be considered in the light of reductions in DOE Nuclear Physics funding, down by 2% in FY1994, which would fall by an additional 14% if the Administration's request for FY1995 were implemented. This report presents NSAC's response to the current charge.

The United States leads the world in nuclear physics, thanks to the consistent support of the Executive Branch and the Congress over many years. This support rests on careful long range planning by the Department of Energy and the National Science Foundation in consultation with the community via NSAC. In pursuit of its basic research mission, nuclear science has gained important new insights into the nature of matter, developed advanced technologies, and provided research, education, and technical training opportunities at all levels.

Major advances in nuclear physics are being achieved in key areas associated with the priorities set forth in earlier Long Range Plans. Excellent progress is being made in all of the high-priority programs, and we are on the verge of bringing into operation major new facilities that will enable exploration of new areas of research. In the study of nuclei near the limits of their stability, new phenomena such as a neutron halo and superdeformed shapes have been discovered, and new instrumentation such as Gammasphere (just beginning operation) promises a very productive future in this area. Novel radioactive beams are enabling the study of exotic reactions that are key elements in understanding the synthesis of nuclei in stars. New techniques and instrumentation have shed light on the structure of nuclear matter in terms of its fundamental building blocks, quarks and gluons, and a premier new facility, the Continuous Electron Beam Accelerator Facility (CEBAF), is poised to begin research in this area next year. Neutrinos that arise from the main energy-producing reaction in the center of the sun have been detected for the first time, and major new experiments such as the Sudbury Neutrino Observatory (SNO), are under construction to study the puzzling deficit in the neutrino flux. In high energy collisions of large nuclei, hot nuclear matter with densities many times normal and approaching the conditions at the beginning of the universe, has been created. Further exploration of extremely hot, dense matter will be possible with the Relativistic Heavy Ion Collider (RHIC) facility, presently under construction. In these studies we expect to produce a new form of matter never before observed: a quark-gluon plasma.

Technological advances, spurred by the demands of the nuclear research agenda, are now in use as research and analytical tools in fields ranging from medicine and environmental science to art and archaeology. These new technologies have also found direct practical applications ranging from integrated circuit production to weapons verification. Emerging applications of nuclear technology show great potential for continuing to address the needs of the nation.

Nuclear physics supports DOE in its commitment to improving scientific and technological education. The program produces a large number of young scientists who help sustain American leadership in science and technology and who possess knowledge and skills of broad importance to society. The nuclear physics community has also taken responsibility for helping, in the long term, to diversify the technological and engineering workforce and to increase public literacy in science.

These scientific, technological and educational activities supported by the nuclear physics program contribute directly to fulfillment of DOE's science and technology mission. Fundamental knowledge is generated in a discipline central to the agency's responsibilities, leading-edge facilities and technologies are advanced, and world-class scientists are produced. Each of these activities represents a substantial contribution to sustainment of DOE core competencies.

The scientific and technical progress has been achieved as a direct result of careful planning by DOE and NSF, with the advice of NSAC. The DOE funding level has been relatively stable and predictable through FY1993. To permit the construction of new facilities despite stringent budgetary pressures, other facilities have been and will continue to be phased out in accordance with the Long Range Plan developed by NSAC in concert with the agencies. In FY1993 the Bevalac at Berkeley was turned off. The Los Alamos Meson Physics Facility (LAMPF), the nuclear physics facility with the largest user community in the nation, was scheduled to be phased out in 1996, after completing important experiments in FY1994 and FY1995. The construction of RHIC was stretched out to sustain important science now, at the cost of a two-year delay in the unique RHIC scientific program.

The precipitous reduction in funding proposed in the Administration's FY1995 Budget request places at risk both the orderly and cost-effective progression of science and the nation's leadership position in nuclear physics. This reduction constitutes a major break in the continuous and successful partnership between the agencies and the research community. Considerable research time will be lost at all DOE facilities. LAMPF will be abruptly phased out as a nuclear physics facility, with key experiments half-finished. User groups, most of them from universities and many supported by NSF, will be severely affected. About 10% of the overall scientific staff (including students) will be lost in FY1995 alone. Such sudden fluctuations and shifts in funding of scientific research are detrimental to a world-class program and are wasteful of the nation's investments.

NSAC has reexamined the budget requirements for carrying out the program so as to achieve the key scientific, technical, and educational goals with prudent use of the nation's resources. *Highest* priority is placed on carrying out the research program, to which the community and the agencies, DOE and NSF, are already committed. This includes a strong university program, effective utilization of operating facilities and of CEBAF, now in transition from construction to operations, and sustaining the necessary scientific manpower and student training. *High* priority is given to timely, cost-effective realization of new opportunities through ongoing facility construction and new equipment development. This includes, in particular, augmented funding for RHIC construction and associated detector development, and support for equipment projects at universities and facilities. All considerations for new facility construction, although well motivated scientifically, have been deferred to a future long range planning exercise because of the budgetary stringencies facing the nation.

These considerations lead to an NSAC recommended budget of $353M in FY1995 and $348M in FY1996. This is a lean budget, somewhat below the lowest planning level presented to NSAC in 1992, but it should be adequate in the near term for maintaining world leadership in this important area of fundamental research.

II. NUCLEAR PHYSICS: THE CURRENT PERSPECTIVE

II.A. The Goals of Nuclear Physics Research

The overarching goal of the nation's nuclear physics program can be summarized as follows:

Understanding, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and in the cosmos, and the forces which govern its behavior.

This entails:

- Development of new technologies and advanced facilities for progress at the nuclear physics knowledge frontier.

- Education of young scientists and training of a technical workforce in the science and technology of nuclear research.

- Significant contribution to the broader science and technology enterprise through the many intersections of nuclear physics with other disciplines.

Clearly, the principal aim of basic research in nuclear physics is to understand the properties and behavior of atomic nuclei and of their proton and neutron constituents (nucleons). Such strongly interacting matter makes up more than 99.9% of the observed mass of the Universe. Nuclei display a remarkable range of phenomena, involving collective motions of the closely-packed strongly interacting constituents and yet surprisingly regular motion of individual nucleons. New facilities and experiments provide unprecedented precision in dissecting nuclear structure, new opportunities to study nuclei at their limits of temperature, pressure or rotation, and the production of exotic nuclei of great interest to astrophysics as well as to stringent tests of our current theoretical understanding.

The realization that nucleons are themselves many-body systems composed of quarks and gluons has produced new challenges and new opportunities for nuclear physics. The underlying description of quark and gluon interactions appears to be in hand through the theory called quantum chromodynamics (QCD). However, the way in which QCD leads to quark and gluon confinement on the scale of about 10^{-13} cm and to the strong forces between nucleons is only beginning to be understood. These intimately intertwined issues are very much at the center of nuclear physics. The structure of matter at very small distance scales and its behavior at extremely high temperatures and densities will be understood only at the level of quarks. That understanding will be pursued aggressively in this decade through the opportunities provided by major new facilities.

Nuclei and the tools of nuclear physics often provide unique opportunities to probe the limits of the Standard Model, which describes nature's fundamental particles and forces. A historical example is provided by nuclear beta decay, the radioactive decay of nuclei due to the weak interaction. The understanding of these processes was an important contributor to the construction of the Standard Model for the electroweak interaction. Despite its many successes, the Standard Model is recognized to be incomplete. The high energy physicists' thrust toward much higher energy accelerators appears to be essential for ultimately resolving these issues. However, the complementary approach of precision measurements at low energies may provide critical clues, and a number of nuclear physicists are pursuing novel experiments in this area.

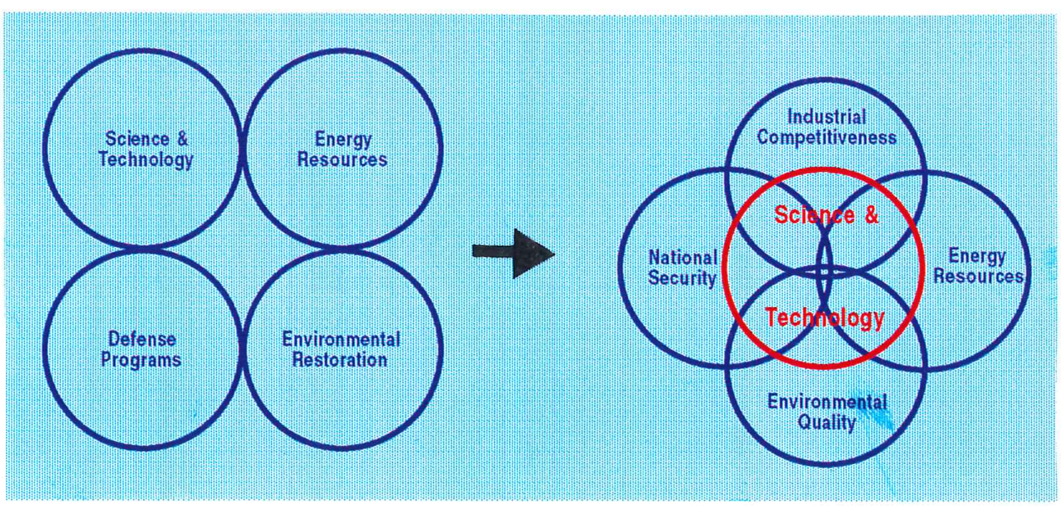
As for most branches of fundamental science, advances at the nuclear physics frontier often depend upon the development of new technologies. Sometimes the new technologies come from other parts of science and engineering. Often, nuclear physicists themselves develop the new technologies or adapt and extend the advances of others. The impact of nuclear physics and its associated technologies is of importance to the nation's economy, health, and security, as well as to other sciences. For example, the origin of one of the most powerful non-invasive medical diagnostic tools, magnetic resonance imaging (MRI), lies in nuclear physics. More recently, developments in accelerator technology, particle detectors, isotope production, and large data handling systems are having enormous impact. The development of large scale superconductivity applications in such accelerators as ATLAS and CEBAF, promises both important science and important future societal benefit.

Education of the next generation of scientists is a very important corollary of fundamental research. Nuclear physics research yielded about 15% of the physics Ph.D.'s awarded in the United States in FY1993; DOE's nuclear physics program is responsible for a large fraction of these, both through direct support and through the support of essential user facilities for research. The majority of these young scientists establish careers in industry and national laboratories, pursuing the nation's strategic goals and contributing directly to DOE's core competencies.

Nuclear physics has important intersections with other areas of science, to mutual benefit. Nuclear processes are central to many important questions in astrophysics: stellar structure and nucleosynthesis depend on nuclear reactions in stars; the nuclear equation of state is central to our understanding of supernovae and of the emission of gravitational radiation in binary systems; the early evolution of the universe involves the QCD phase transition. The intersection with particle physics has already been discussed, both at the "low energy frontier" of the Standard Model and in the common interest to understand nucleon structure, albeit with different emphases. Nuclei provide an important laboratory for studying chaos and nonlinear dynamics in the quantum regime. The theoretical description of many-body systems is driven by fields as diverse in their scientific goals as condensed matter physics and nuclear physics; for example, the theory of mesoscopic systems and metallic clusters profits from a multidisciplinary interest. These intersections promote the American scientific community's attempts to advance broadly at the scientific frontier.

II.B. Contribution to the DOE Mission

The April 1994 Strategic Plan of DOE presented a new focus and a reshaping of missions, priorities and business practices. The science and technology "business" of the DOE was identified, even more strongly than in the past, as a core activity. This is seen in the following figure from the DOE Strategic Plan:



The vision expressed for science and technology is:

> "Science and Technology provide the knowledge that drives our future. World-class scientists and engineers, working in world-class facilities on leading-edge problems will spawn the knowledge that revolutionizes technology - the knowledge and technology that others need to achieve their vision."

This statement was amplified through five specific goals:

- Provide the science and technology core competencies that enable DOE's other businesses to succeed in their missions.
- Provide new insights into the nature of matter and energy, address challenging problems, and create a climate in which breakthroughs occur.
- Construct leading-edge experiments and user facilities on schedule, within budget, and in a safe and environmentally responsible manner.
- Add value to the U.S. economy through the application of new and improved technologies.
- Help provide a technically trained and diverse workforce for the nation and enhance American scientific and technical literacy, especially in energy, the environment, and the impact of science on the economy.

Clearly, it is important that the nuclear physics program contribute to DOE's science and technology goals. As already outlined briefly in the last section, nuclear physics does indeed contribute in an important way to each goal. This will be amplified in the more detailed discussion of Chapter III.

II.C. The Planning Process

Partnership between the nuclear science community, the Department of Energy, and Congress is needed to meet the science, technology and educational goals of the program and to advance the DOE mission. The key element of this partnership is the NSAC Long Range Plan process. The Long Range Plans of 1979, 1983 and 1989 have identified the key science initiatives, set priorities within realistic budgetary constraints, and provided the framework for NSAC response to specific charges in the intervening years. The process has helped ensure world leadership for the U.S. nuclear physics program, while the community has shown considerable coherence and has accepted the need to phase out programs in order to pursue new opportunities within fiscal constraints. For example, recently two very large facilities, the Bevalac and LAMPF, have been or will be phased out as national nuclear physics user facilities.

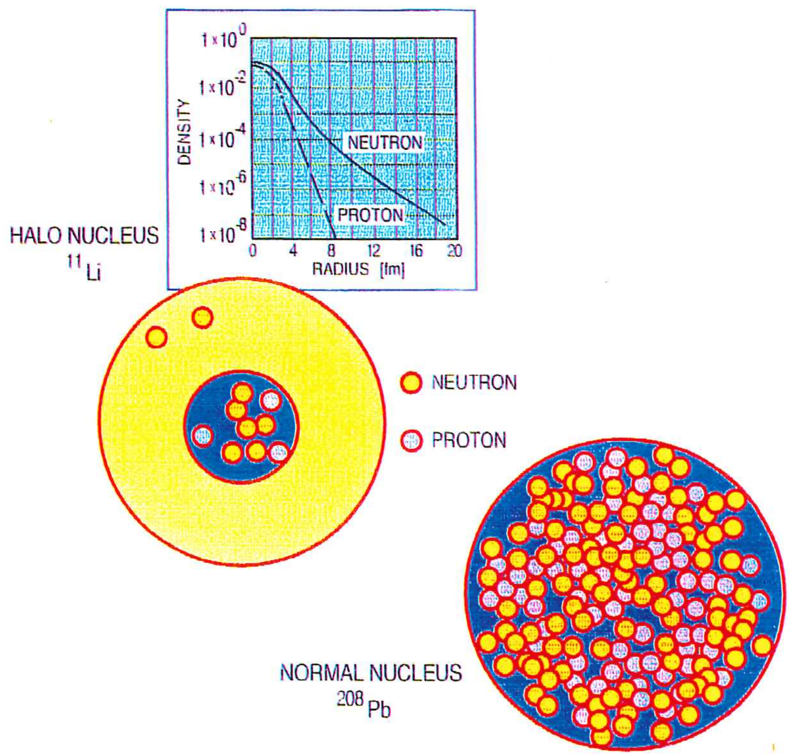
Needless to say, this process succeeds so long as priority setting does not become equated with budget cutting. Regrettably, part of the background for this report is an apparent departure from the highly successful long range planning process in the FY1995 Administration request for DOE nuclear physics funding. As recently as 1992, the worst-case DOE guidance to NSAC for nuclear physics funding was constant as-spent dollars of $363M. The precipitous drop from the FY1994 appropriation of $349M to the FY1995 request of $301M, if enacted, obviously would cause major dislocations in the program. In this report, we evaluate the status of nuclear physics with respect to Long Range Plan priorities and the resources needed to carry out the program in a cost- effective and scientifically effective manner.

The NSAC process has been instrumental for guiding inter-agency cooperation in advancing nuclear physics. The National Science Foundation supports a large number of university researchers, many of whom depend upon DOE-supported nuclear physics user facilities for their research opportunities. Such researchers help provide intellectual leadership at those facilities and often contribute substantial resources to the experimental apparatus. Thus, although this charge to NSAC primarily involves the DOE nuclear physics program, we note the impact of DOE plans for nuclear physics on the entire research community

III. SCIENCE, EDUCATION, AND TECHNOLOGY

III.A. Nuclear Science: An Evolving Frontier

Nuclear Physics Research embraces fundamental studies of the properties of nuclei, the characteristics of their microscopic building blocks, and the basic nature of the nuclear force. Nuclear structure is dominated by the strong interaction but the electroweak interaction also plays a crucial role in limiting nuclear stability. Nuclear physics is concerned with fundamental studies into the properties of the 'normal' matter that surrounds us and that we ourselves are made of, as well as those of matter under extreme conditions, such as those found during the early stages of our Universe. In addition to investigations which probe the properties of hadronic matter and the strong force, nuclei serve as unique microscopic laboratories to investigate fundamental symmetries and the physical laws of nature emanating from them. As a consequence of this necessarily broad field of inquiry, a wide range of tools, including accelerators for various types of particles and energies, is needed for world-class nuclear physics research. Recent results and new capabilities from novel instrumentation have opened the new frontiers in this research endeavor.



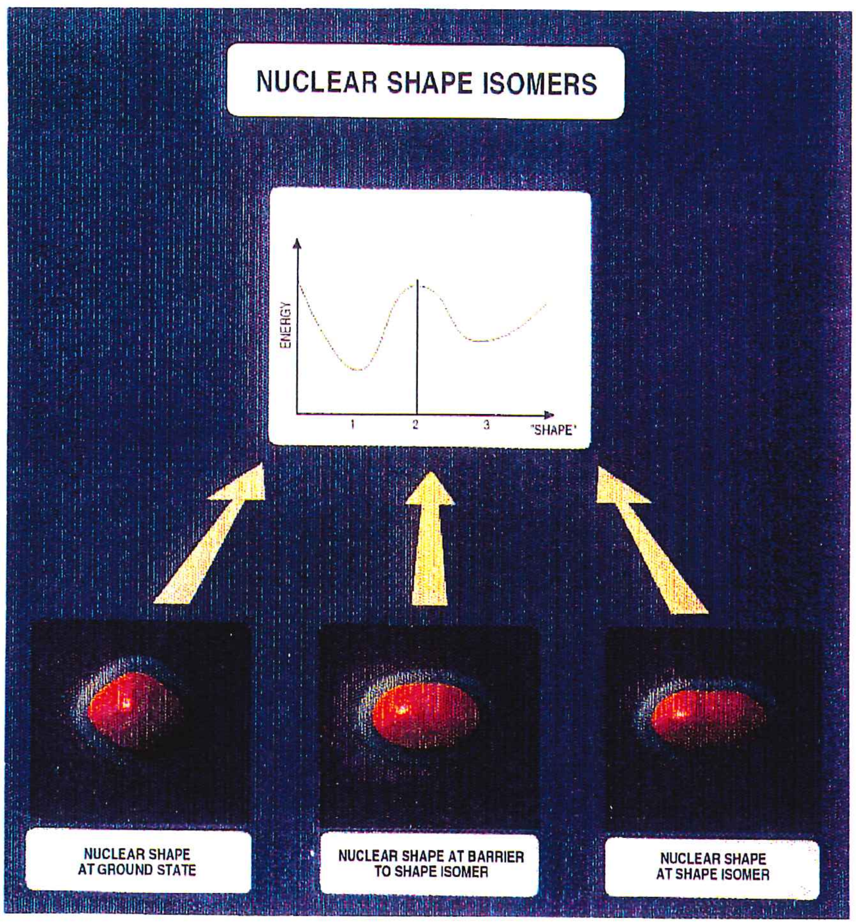
Experiments with radioactive beams have recently identified nuclei with a large excess of neutrons. A few of the neutrons in these nuclei form a "halo" that extends to radii well beyond the central core. This is in contrast to the situation in "normal" nuclei in which the neutrons and protons both occupy roughly the same region in space.

The experimental program advances in concert with the important efforts in nuclear theory. To complement and strengthen the interactions between individual theorists, DOE has recently provided an effective organizational framework for exchanges between different nuclear theory programs in the form of the Nuclear Theory Institute in Seattle. The Institute has also a significant interdisciplinary component for promoting advances at the broader frontier of theoretical physics.

In the remainder of this section, we sketch some recent results and emerging thrusts. We make no attempt at completeness in this brief report, but hope to capture the flavor of several key activities.

III.A.1. Structure and Reactions of Nuclei near the Limits of Nuclear Stability

The binding of nucleons by the strong force is fundamental to the very existence of the Universe as we know it. The evolution of the Universe since the first few minutes of its history has been determined by the aggregation of nucleons to form nuclei, and the synthesis of heavier species by reactions between these nuclei. The stable nuclei that surround us in everyday life constitute less than 10% of all the nuclear systems that should exist. The stability of these nuclei arises from a delicate balance between nuclear, electromagnetic, and weak forces, modified by the many subtleties of strongly interacting systems. Investigations of stable nuclei have provided important guidance to the intricacies of binding. These range from high-precision electromagnetic scattering experiments with electron beams, to scattering and reaction studies with particle beams of protons, pions, and light to heavy nuclei. More recently, the study of unstable nuclei and nuclei under extreme conditions of excitation, temperature, spin, and neutron/proton ratios furthers our understanding of binding, and provides insights into the early phases of the Universe, nucleosynthesis, and exotic astronomical objects.



Stable configurations of nuclei occur when the energy is minimized. In some nuclei which are spherical or nearly spherical in their ground state, the interplay between independent particle motion and collective modes can give rise to a second stable configuration (with a local minimum in energy) at very large deformations. This highly-deformed, stable shape can be reached by spinning the nucleus very rapidly.

The theoretical solution of the general nuclear binding problem, with large numbers of nucleons and many possible quantum states, remains intractable; self-consistent microscopic calculations can be carried out reliably only for the lightest nuclei. However, recent advances in computational techniques have generated much progress toward extending these calculations to heavier systems; these calculations are well-suited to take advantage of developments in massive parallel computing.

Nuclear reactions have played a central role in the exploration of the properties of nuclei. Recent progress in both technical capabilities and theoretical understanding have allowed us to approach regions at the limits of existence of nuclei: the limits for binding of nuclei with large excesses of neutrons or protons; the fastest rotations that nuclei undergo before breaking up; and the maximum thermal energy that a nucleus can hold before it evaporates into fragments and nuclear constituents.

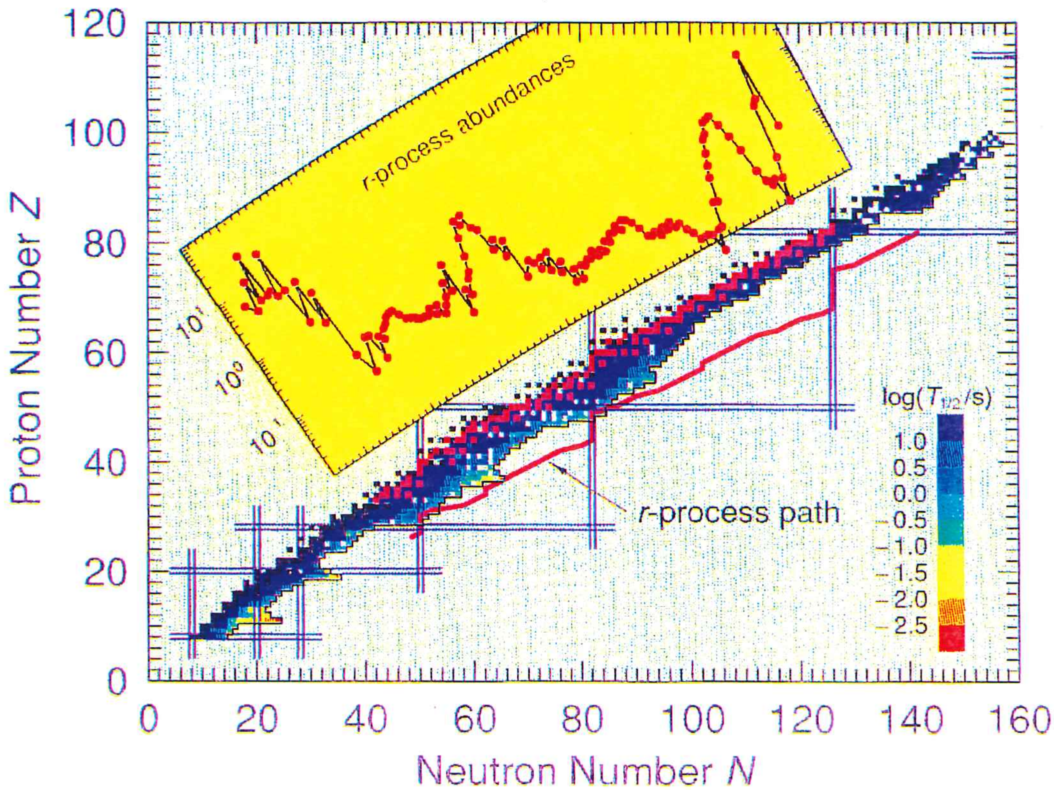
In light nuclei with more neutrons than their stable counterparts, it appears that some of the neutrons extend well beyond the bulk of the nucleus to form a halo of neutron matter. This decoupling of neutrons from the normal nuclear core, a situation not found in stable nuclei, allows for the possibility of creating new modes of excitation and the challenge of understanding the stability of neutron-rich nuclei.

We have also developed the technology for synthesizing medium weight proton-rich nuclei, near the "proton drip" line; in these systems it is the protons that are very loosely bound to the bulk of the nucleus. The resulting proton radioactivities provide some of the most challenging tests of nuclear models, as they depend sensitively on both the overall binding energies and the quantum mechanical characteristics of the least-bound states.

In the heaviest nuclei, we continue to learn about the competition between binding effects from the nuclear force, strongly influenced by the quantum mechanical shell structure of nuclei, and the electromagnetic repulsion which leads to fission. What was originally thought to be a gap in the sequence of elements leading to the region of the heaviest nuclei is now known to be a region containing many new isotopes which gain stability through deformation. It is now thought that heavy nuclei with measurable lifetimes exists for up to ten elements above the heaviest ones known, and for about 400 isotopes (i.e. nuclei of the same element and thus nuclear charge but with different neutron number). However they are difficult to produce in nuclear reactions. Studies are under way with heavy-ion beams to find the best access to this new region of the charts of the chemical elements and of nuclei.

Nuclear shapes with unusually large elongations have been observed by inducing nuclei, which are essentially spherical in their ground states, to rotate rapidly. Such "superdeformation" occurs because the interplay between independent particle motion and collective modes gives rise to new regions of stability at very large prolate deformations. Experiments with new multi-counter detection systems have revealed an unexpectedly rich array of new properties for these systems. One of the most striking results led to the observation that nuclei differing by one or more mass units may possess almost identical gamma-ray decay sequences. This phenomenon, also recognized recently in normal nuclei, has not yet been explained.

Nuclear reactions provide a means to produce nuclei far from stability which are crucial to our understanding of the evolution of the Universe and yield insights into many areas of current astrophysical interest such as the "Big Bang", supernova explosions, neutron stars, and the chemical composition of the Universe. New results on reactions of astrophysical relevance have been obtained through the use of radioactive secondary beams. Fundamental properties governing the reaction cycles that produce carbon, nitrogen, and oxygen have been measured for the first time. These are the most abundant heavier elements beyond hydrogen and helium in the Universe, and form the basis for life. Radioactive beams holds great promise for exploring other questions of importance to astrophysics, such as the "breakout" rapid proton capture process (rp-process) that opens the way for nucleosynthesis from the cycle governed by the elements just mentioned to the production of heavier elements, such as calcium and other heavy trace elements that are indispensable for the evolution of intelligent life on Earth. Radioactive beam studies are critical to our understanding of the rapid neutron capture process (r-process), which generates all elements heavier than iron, the most stable nucleus.



The ratio of the number of neutrons to protons in stable nuclei slowly increases from about one (in light nuclei) to nearly two to one (in heavy nuclei). These nuclei lie in the "valley of stability" shown on the figure. The synthesis in nature of nuclei heavier than iron (26 protons) occurs mainly through the rapid neutron capture process (r-process). This process occurs during explosive star burning where large number of neutrons are available, and involves nuclei far from stability. Radioactive beams provide the means to synthesize and study in the laboratory the highly unstable nuclei that lie along this path.

The radioactive ion beams now available are severely limited in intensity, species and quality. Nevertheless, they have opened a new dimension in nuclear structure research. Because of the promise of these beams for both research and technology, an active user community, the Isospin Laboratory (ISL) User Group, has formed and identified opportunities for their use. A white paper ("The Isospin Laboratory – Research Opportunities with Radioactive Beams") has been produced in support of a major future facility.

Highly excited nuclear matter, generated by nuclear reactions between heavy nuclei at elevated energies, forms the underpinning for studies of nuclei under limiting conditions of pressure and temperature. Central, head-on collisions completely stop the penetrating nuclear ensembles. The hot compressed systems formed by these reactions expand rapidly and reach nuclear densities well below normal. The transition from a dense, liquid nuclear medium to a loosely interacting, gas-like phase is the object of intensive studies at various heavy-ion facilities. Studies of multi-fragmentation show that the breakup process for very hot nuclei is quasi-spontaneous, and distinctly different from the statistical, evaporation-like processes observed previously in systems that had not reached limiting temperatures. Many features of these processes are yet poorly understood.

In summary, recent experiments on nuclei at the limits of stability have uncovered new and unexpected manifestations of the nuclear medium. Newly developed capabilities will allow considerable progress in pursuing the new ideas these experiments have generated and the questions they have raised.

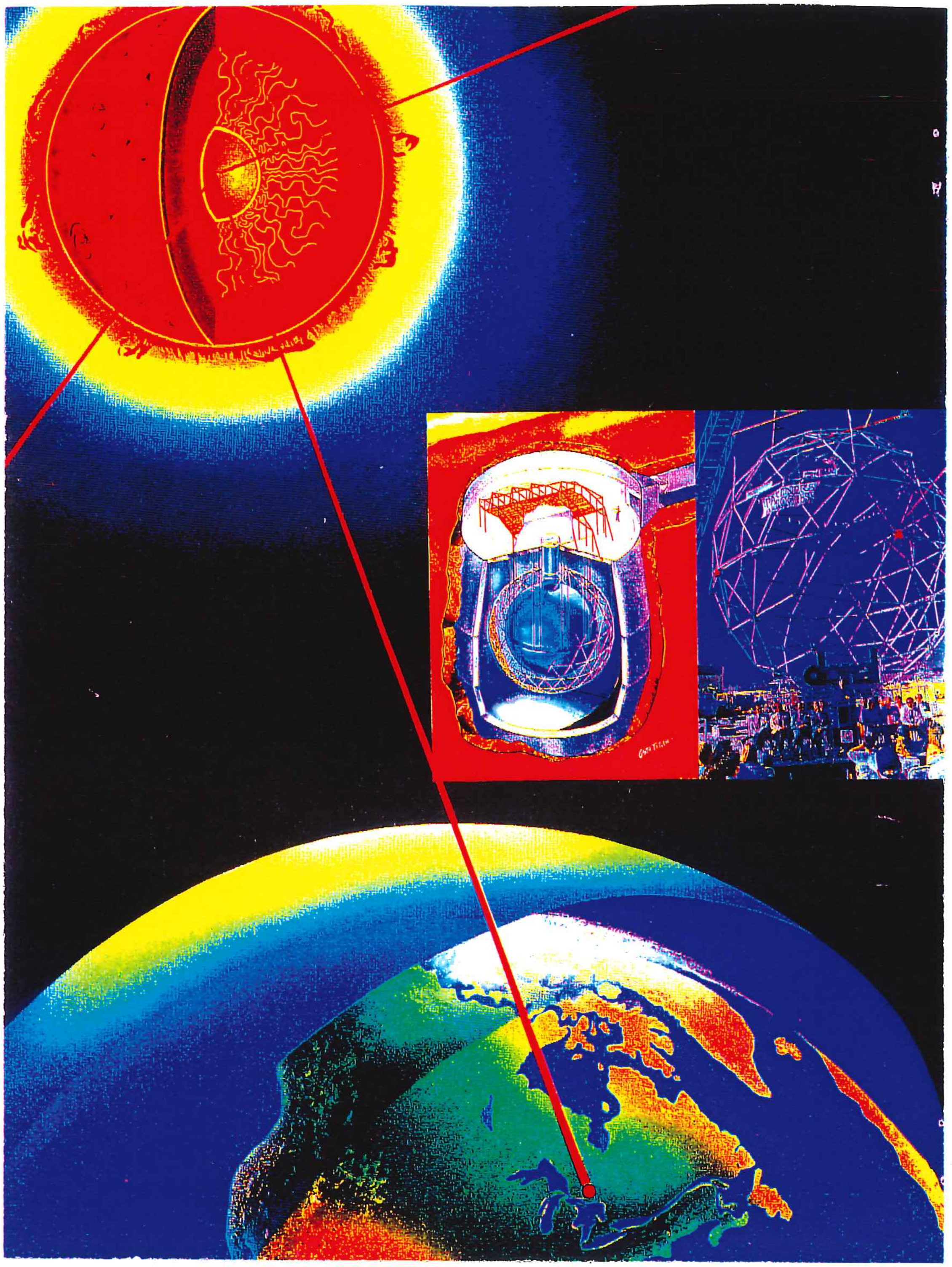
III.A.2. Precision Experiments with Nuclei: Neutrinos, Weak Interactions and the Search for New Forces

Neutrinos, probably the most mysterious of the known particles, are extraordinarily elusive; a neutrino produced in nuclear beta decay can easily pass through a "light year" of lead without interacting. This property is due to that fact that neutrinos only interact with matter via the "weak" force. As a consequence, there are many basic questions about neutrinos for which there are no firm experimental answers. Do neutrinos have a mass like most other particles or are they massless like the photon? Are neutrinos their own antiparticles or are antineutrinos distinct from neutrinos? Can one species of neutrino, say the electron neutrino, spontaneously evolve into another species, say the muon neutrino? Why is the number of neutrinos coming from the sun smaller than expected?

Many of these questions are related. For example, the nuclear reactions that power the sun are a copious source of neutrinos, and these neutrinos provide us the only way to see directly into the center of the sun. All other forms of radiation are absorbed long before they can escape. Nevertheless, there is a connection between the observed brightness of the sun and the rate of nuclear reactions in the solar interior which produce the solar neutrinos. The first experiment to detect neutrinos from the sun was located in a mine in South Dakota and used the inverse nuclear beta decay reaction on ^{37}Cl. It discovered that the measured flux of neutrinos was significantly lower than the expected number based on the sun's brightness. Since then experiments have been mounted all over the world to study different energy solar neutrinos by using a variety of nuclear reactions. All of these other experiments have detected a deficit in the number of solar neutrinos although the ratio of observed to expected flux seems to depend on the neutrino energy. There are several intriguing explanations for this important result. One possibility is that the missing solar neutrinos were emitted as electron neutrinos, but then evolved into another species of neutrino on their journey from the center of the sun toward the earth-bound detectors. This, in turn, would require that the neutrinos have a mass and that neutrinos can change spontaneously from one species into another. Such a result will have profound consequences for the Standard Model of particle interactions.

These and other fundamental questions about neutrinos are currently being investigated in a variety of nuclear physics experiments. The Sudbury Neutrino Observatory (SNO), under construction in Canada with major U.S. involvement, consists of a large heavy-water detector located deep underground in a nickel mine. This powerful device for studying solar neutrinos will be able to accurately measure energies of the solar neutrinos, and also to count those neutrinos that may have evolved into other species on their journey from the center of the sun. The results from the SNO detector should tell us whether neutrinos evolve into other species while passing through the interplanetary space (so-called vacuum oscillations), or whether they also experience an enhanced evolution rate while passing through the solar medium, the so-called MSW effect, or whether there are basic properties of the sun that are simply not understood as well as had been thought.

Neutrino evolution is also being studied in laboratory experiments using particle accelerators or nuclear reactors as sources of neutrinos. Researchers produce one species of neutrino and look for it to spontaneously evolve into another species as it travels between the source and a neutrino detector (such as the LSND at LAMPF). Such experiments probe very different ranges of neutrino masses than do the solar neutrino experiments.



Neutrinos are emitted by a number of the energy-producing nuclear processes deep inside the sun. Because of their weak interaction with matter, these neutrinos penetrate the sun and carry information on these reactions to earth, where one measures them in specially-constructed detectors. The Sudbury Neutrino Observatory (SNO) is the latest of these detectors; it is designed to provide new information on these reactions and on the behavior and nature of the neutrinos themselves.

One can also learn about neutrinos by studying one of the rarest known processes, double beta decay of nuclei. These experiments can test whether neutrinos are really distinct from their antiparticles and whether they have a mass. Because double beta decay is such a rare process, detectors designed to study this process must contain large numbers of nuclei that are capable of double beta decay and the counting scheme must have extraordinarily low levels of background radioactivity. Recent work with large germanium detectors enriched in the isotope ^{76}Ge has reached impressively high levels of sensitivity, and further work is in progress.

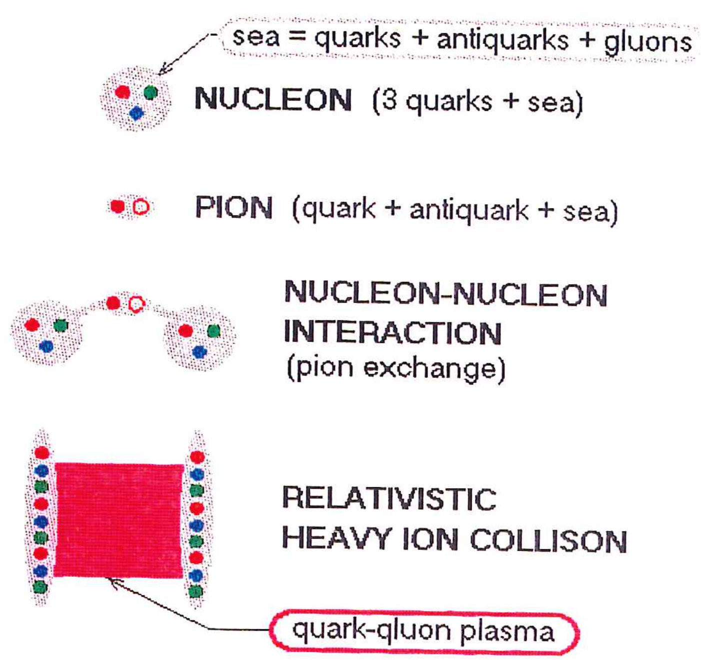
The weak force is of fundamental significance in nuclear physics. It is a major determinant of the nuclear "valley of stability." The first step in the chain of nuclear reactions that are responsible for energy generation in the sun is due to the weak interaction. This force also plays a key role in nucleosynthesis in supernovae and in many tests of our understanding of nuclear structure. Precision nuclear physics experiments are a very important part of the effort to understand this force.

In the accepted theory of the weak force (Standard Electroweak Theory), the interaction is different for mirror-image processes. This property, called parity violation, was first demonstrated in nuclear beta decay experiments many years ago and shapes the character of the Standard Electroweak Theory, but the underlying origin is still not understood. Many new theories speculate that the interaction becomes symmetric again at very high energies, higher than we can now probe in the laboratory. This is analogous to the way the asymmetric north and south poles of a magnet disappear at high temperatures when the material loses its magnetism. By performing precise experiments in muon and in nuclear beta decay, one may detect this new property of the weak force and thereby study the theory beyond the highest energies that can be reached by even the largest particle accelerators. The Standard Electroweak Theory also predicts that the weak force slightly violates time-reversal symmetry, and the detection of this property in nuclear beta decay would be an extremely important test of the theory. Several novel experiments are in progress to further investigate properties of the weak force and to search for signals of new, perhaps even weaker, forces.

III.A.3. The Quark Structure of Matter

The suggestion of Yukawa that the nuclear force between neutrons and protons (nucleons) is due to the fleeting exchange of π-mesons (pions) was a key step in understanding the nuclear interaction. Over many years, the sophisticated phenomenology of the nuclear force developed using the pion and heavier mesons has provided a rather successful description of many nuclear observables. For example, electron scattering from nuclei (in effect, very high resolution electron microscopy) has yielded quantitative insight into the motion of individual nucleons responding to the influence of the forces exerted by the other nucleons in the dense nuclear medium. Experiments of this type have even detected mesons "in-flight" between the nucleons.

We know that our picture of nuclei and the strong interaction based on nucleon and meson exchange, despite its many successes and predictive power, is incomplete and valid only over a limited range of conditions. Quantum Chromodynamics (QCD) provides the basis for a more fundamental description and for extending our understanding of matter into new regimes. Experiments at high energies have demonstrated conclusively that nucleons and mesons are composite objects made up of point-like particles called quarks (and their antiparticles, the antiquarks), interacting via the exchange of gluons. At first glance, QCD appears to be similar to the best understood fundamental interaction, Quantum Electrodynamics (QED), which describes the interaction between electrons via photon exchange and provides the basis for our understanding of atoms, molecules, and solids. However, the gluons of QCD are strongly self-interacting. A consequence appears to be confinement: quarks and gluons cannot appear in isolation ("free") except under extremes of temperatures (~10^{12} degrees Kelvin, a temperature not reached since the first microseconds after the Big Bang) or density (many times normal nuclear matter). Thus, the strong interaction between nucleons is really the residue of the quark and gluon confining interactions inside the nucleons. When the nucleons are far enough apart, this residual interaction is approximated by the exchange of pions. However, QCD is essential to the description of the important regime of separations comparable to or less than the confinement scale (~10^{-13} cm). Therefore, the internal structure of nucleons and mesons and the strong interactions between them are completely intertwined and represent a central line of inquiry in nuclear physics.



Nucleons have internal structure: three "valence" quarks immersed in a "sea" of gluons and quark-antiquark pairs. At large distances, the strong interaction between nucleons is described by the exchange of pions, but when we look at nucleons or nuclei with high resolution (or high energies) their internal structure becomes evident. Theoretical studies also indicate that by colliding two heavy nuclei (with hundreds of valence quarks and a sea) at high energies, we can heat nuclear matter to very high temperatures, and create a quark-gluon plasma in which the quarks are free.

These are difficult problems, but their solution lies at the heart of understanding strongly interacting matter in its various manifestations. An extensive set of complementary experiments, using electron, meson and nucleon beams and new target and detector technologies will be required. The nearly completed CEBAF is expected to have a major impact on these issues. It provides the precision of the electromagnetic probe with an unprecedented combination of very high intensity and 100% duty factor at energies of several GeV (providing spatial resolution of about a tenth the size of the nucleon). Important rare processes will become accessible for the first time. CEBAF will be the world's most powerful "electron microscope" for the study of nuclei and the strong interaction. An entirely different set of complementary experiments aimed at studying de-confined quarks and gluons will use relativistic heavy ion beams; this is discussed in the next section. Advances in nuclear theory will also be critical. New tools such as the teraflop computational capability expected to be available in a few years, will permit the simulation of QCD on a lattice of space-time points. The interplay of all these approaches suggests very exciting science for the years ahead.

The structure of the nucleon remains a major challenge to our understanding. For example, the distribution of electric charge within the neutron is not yet known with sufficient precision to constrain QCD-based models. Similarly, the deformation of the nucleon when the spin of one of its quarks is flipped is not known; this deformation is sensitive to the quark-quark interaction inside the nucleon. The more highly excited states of the nucleon are called N*'s.

Simple quark models of nucleon structure, with little of the full content of QCD, are remarkably successful in characterizing the lowest energy states, presumably because the gluonic degrees of freedom remain inactive. CEBAF will open up new possibilities for studying higher excitations, where the gluonic degrees of freedom should come into play, and thereby open up new avenues for understanding how QCD manifests itself in "cold "matter.

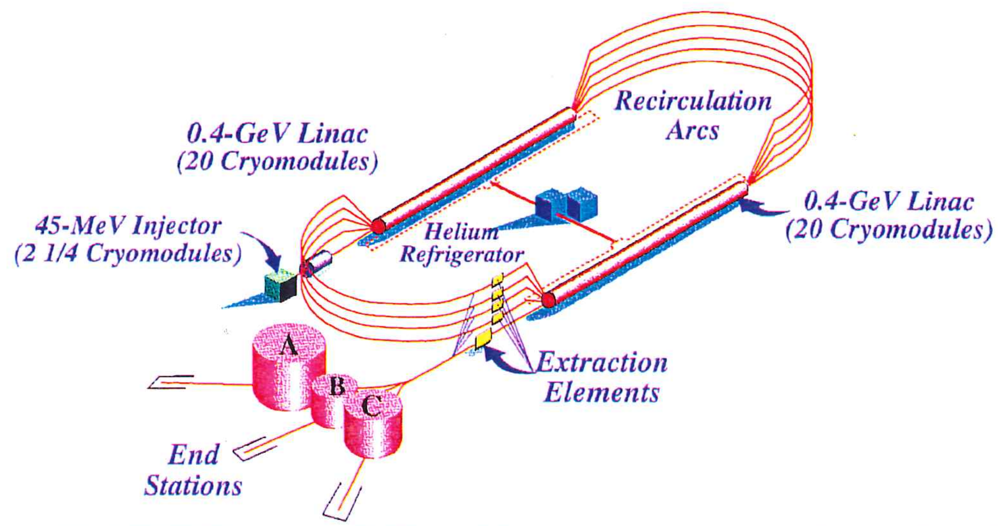
The three valence quarks of the nucleons carry with them a sea of gluons and quark-antiquark pairs. A major focus of current work has been the study of this sea in nucleons and nuclei; there is growing evidence that this sea cannot be understood as a weak QCD perturbation on the valence structure, but rather must arise in part from the very strong confinement effects. One subject that has received much attention in recent years is the spin of the nucleon. Some experiments indicate that the quark-antiquark sea plays a very important role in the origin of the spin of the proton. In fact, it appears that the spin of the valence quarks is canceled, to a large extent, by that of the quark-antiquark sea. This result is very surprising and has motivated a substantial number of new experiments. In particular, it is critical that similar measurements be performed on neutrons, requiring the use of polarized nuclei. Another important question is the relative number of different types of antiquarks in the sea. For example, it would be interesting to know the ratio of the number of "down" antiquarks to the number of "up" antiquarks. There is new experimental evidence that this ratio is significantly different from unity, in rough agreement with the older meson picture. These experiments, which have important implications for the dynamics of the sea are generally carried out by collaborations of nuclear and particle physicists.

As already noted, the interaction between two hadrons is intimately related to the confinement mechanism. Because the deuteron is the simplest bound system of hadrons it is the focus of many studies. Spin-dependent elastic electron scattering has probed rather short distance scales in the deuteron without finding the limits of the nucleon-meson picture. On the other hand, investigation of the photodisintegration of the deuteron at high energies has shown the behavior expected on the simple grounds of counting the number of point-like quarks in the deuteron. These apparently contradictory examples emphasize our current inability to bridge the gap between the phenomenological nucleon-meson and the more fundamental quark-gluon descriptions. Experiments at CEBAF are expected to contribute in a major way towards bridging this gap in our understanding of nuclear interactions and structure.

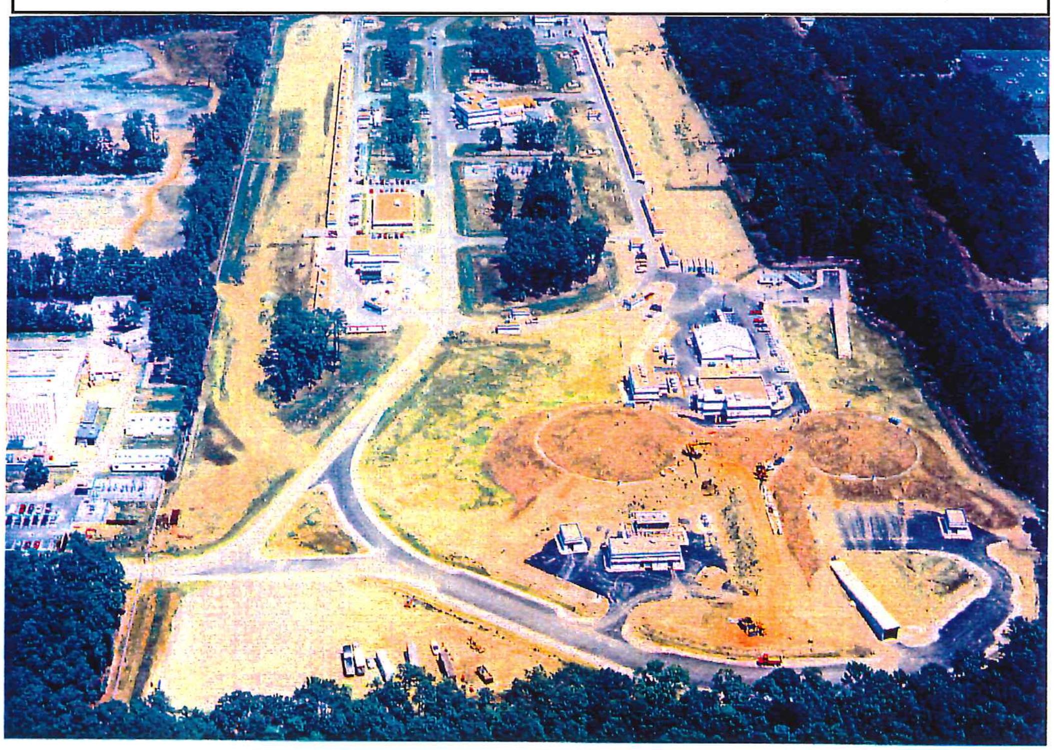
The nuclear environment also provides a unique opportunity for testing various aspects of QCD and guiding our theoretical development. A recent experiment studied the prediction of "color transparency". With large momentum transfer from an electron to a proton inside a nucleus, the QCD-based expectation is that the struck nucleon should find the nucleus remarkably transparent to its escape. However, our incomplete understanding of QCD leaves considerable uncertainty in the prediction of the scale at which this phenomenon sets in strongly and, the experiment found the opaqueness anticipated from the nucleon-based picture even at rather large momentum transfers. Similar experiments will be extended to even higher momentum transfers in the future.

As with the study of other many-body systems, such as solids, it is often illuminating to introduce and study impurities. Normal matter is presumably dominated by the light up and down quarks. The study of strange quarks in nucleons and nuclei has barely begun, but is expected to be very important. One class of experiments uses the electroweak interaction to isolate strange quark contributions from the sea. For example, the active experiments SAMPLE and LSND use low energy polarized electrons and neutrinos, respectively, to provide unique measures of the strange quark contribution, complementary to those accessible at high energy facilities. Another approach is the use of meson beams to inject strange quarks into nuclei. The resulting "hypernuclei", which do not normally occur in nature, can reveal much about the interactions of nucleons and hyperons (baryons with a strange quark). These studies follow, in

MACHINE CONFIGURATION



Schematic layout and photo of the Continuous Electron Beam Facility (CEBAF), the premier new facility in nuclear physics just beginning commissioning activities. Beam from the injector is passed five times through a pair of 400 MeV superconducting linacs before being split and sent to three experimental halls. The helium refrigerator which cools the linacs is the largest in the world at 2 degrees Kelvin.



spirit, the extensive studies carried out using pions which revealed much about nuclear structure and about the interactions of excited nucleons. In the absence of an intense multi-GeV hadron facility, the opportunities in this area will be limited, although some progress will be forthcoming from strangeness production experiments using electron and proton beams. A large group of nuclear and particle physicists have held workshops to explore options available now and initiatives for the future for advancing this science.

Clearly, we have made much progress in the last few years towards understanding nuclear physics and nucleon structure in terms of QCD. Key experimental and theoretical issues have been identified and a new array of experimental and theoretical tools are being readied to explore this important frontier of modern nuclear physics. The next decade promises to be a very exciting and productive one as we approach our goal of a fundamental understanding of the origin of nuclear forces and the structure of the constituents of the atomic nucleus.

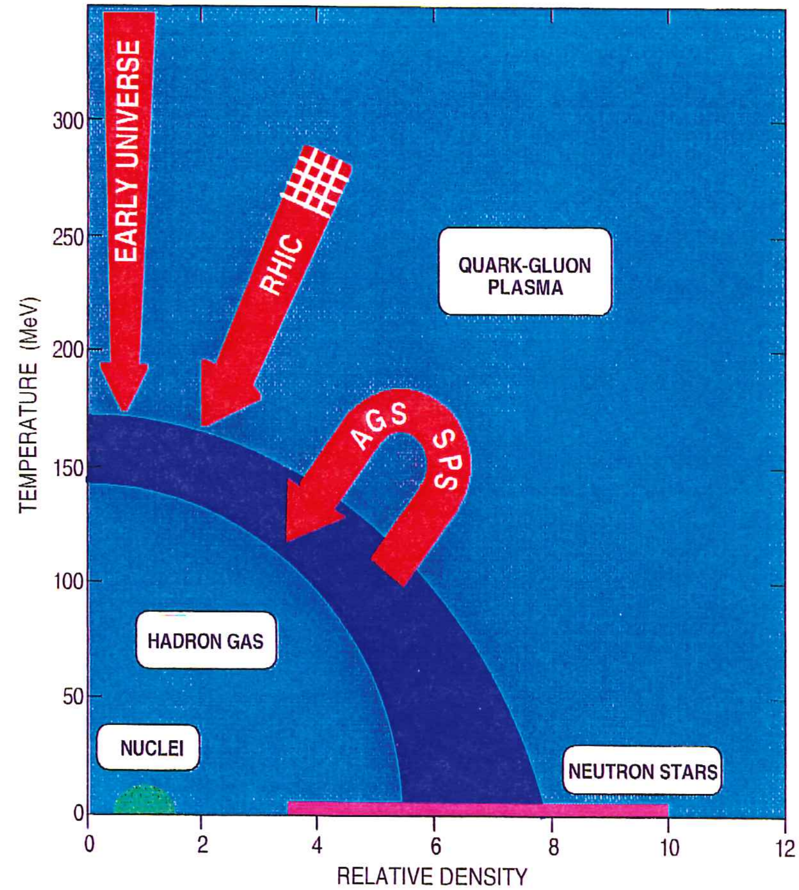
III.A.4. Transformation of Nuclear Matter Under Extreme Conditions

Much of our knowledge about the origin of the Universe is derived from a detailed understanding, and comparison with observations, of the processes which occurred during the era of cosmic nucleosynthesis. During this period of an expanding and rapidly cooling cosmos, protons and neutrons coalesced into light nuclei. The prediction and subsequent confirmation of these phenomena represents one of the great intellectual triumphs of nuclear physics. At an even earlier time of approximately ten microseconds after the "Big Bang", the elementary quarks, antiquarks, and gluons condensed into hadrons (baryons and mesons) to form the world of particles we now observe. Before this quark-hadron phase transition the quarks, antiquarks and gluons are believed to have formed a dense quark-gluon plasma. This phase transition is expected to occur at a temperature of 150 to 200 MeV or about 10^{12} degrees Kelvin. Identifying and studying the quark-gluon plasma is the quest of the field of relativistic heavy ion physics.

A similar phenomenon may occur in the interior of collapsed, burned-out stars, commonly called neutron stars. Under the pull of gravity the matter density of these stars can reach many times the density of normal nuclear matter. Theoretical calculations indicate that under such conditions nucleons will dissolve into their elementary constituents to form a cold plasma of quarks which move freely over the entire volume of the star. Cold quark matter is predicted to contain a large fraction of strange quarks.

Today, in collisions of two heavy nuclei at very high energies, nuclear physicists attempt to recreate in the laboratory the transition between matter composed of ordinary hadrons and a quark-gluon plasma. The relation between these laboratory investigations and the phase transitions expected in the early Universe and in the evolution of stars can be understood from the phase diagram of nuclear matter. Normal nuclei can be found at low temperatures and groundstate nuclear densities. The early Universe is believed to have cooled from extremely high initial temperatures and low densities through the quark-gluon plasma phase, finally condensing into hadrons below the transition region in the phase diagram. Neutron stars are found at the other extreme, that of high densities and very low temperatures. Various regions of the phase diagram are expected to be accessible using relativistic heavy ion collisions. High (baryon) density quark matter at a temperature close to the critical temperature for the phase transition may be formed and studied in the current experimental program at the Alternate Gradient Synchrotron (AGS) at Brookhaven. The Relativistic Heavy Ion Collider (RHIC), presently under construction at Brookhaven National Laboratory, will permit exploration of the low (baryon) density hot quark-gluon plasma, similar to that which existed in the early Universe. It remains a challenge to these experiments to uniquely identify the quark-gluon plasma and to determine characteristics of the phase diagram, in particular the phase-transition region.

The theoretical basis for the existence of a transformation from hadronic matter to a quark-gluon plasma has been convincingly established by numerical solutions of QCD on large scale computers ("Lattice QCD"). The transformation is ultimately caused by weakening of the interactions among quarks and antiquarks as their density is increased, leading to a fundamental rearrangement in the structure of the quark vacuum. Chiral (or left-right) symmetry, which is strongly broken in normal nuclear matter, is almost completely restored in the high density phase, where quarks and antiquarks are no longer confined into hadrons. Although much progress has been made in recent years, the microscopic details of this transition are still poorly understood and remain the object of active theoretical research.



The expected phases of nuclear matter, and corresponding astrophysical events when these phases are predicted to have existed, as a function of density (relative to stable nuclei) and temperature. A phase transition (violet region) to a quark-gluon plasma of freely interacting quarks and gluons is predicted to occur at high temperatures and densities. The early Universe is expected to have cooled through this phase transition region to form the world we know today. Regions to be explored in laboratory experiments are indicated by the facilities (AGS, SPS, RHIC) that will accelerate nuclei to the high energies required for these studies.

According to recent theoretical studies, collisions between two large nuclei at high energy lead to a rapid local equilibration of the available energy. This permits the use of the tools of statistical physics and thermodynamics to describe the evolution of these systems of highly compressed nuclear matter, and leads to quantitative predictions of signatures of the phase transition. Examples of such signatures are a strongly enhanced production of strange hadrons, a suppression of heavy quark bound states (such as charmonium), and the spectra of lepton pairs and photons emitted from the hot system. Theorists are presently developing a microscopic description of these nuclear reactions and are improving the reliability of predictions for quark matter signatures.

Creating high density nuclear matter in the laboratory through collisions of relativistic heavy ions has been addressed since the pioneering experiments began twenty years ago at the Bevalac accelerator at Lawrence Berkeley Laboratory. Experiments with much higher energies are currently in progress at CERN in Switzerland and at the AGS in Brookhaven. The AGS experiments have firmly established that most of the kinetic energy of the colliding nuclei at the present beam energies can be converted into compressional energy and heat, creating initial conditions of up to ten times normal nuclear matter density and temperatures close to the predicted phase transition.

Experiments with very heavy beams of mass number around 200 have recently begun at the AGS and are expected to investigate nuclear matter in the laboratory at the highest densities ever, and at temperatures close to or above the critical temperature for the predicted phase transition. Tantalizing preliminary indications for modifications in the structure of hadrons have been observed and will be explored intensively while the AGS has world-wide the unique capabilities to study the heaviest collision systems.

To study the high-temperature, baryon-depleted quark-gluon plasma of the early Universe, the higher energies accessible only with the colliding beams at RHIC are needed. At these energies, gluons are predicted to play an important role in the fast equilibration of the system. It is expected that a very hot plasma will be formed with an initial temperature close to 400 or 500 MeV. This hot plasma is also close to the regime that can presently be calculated using Lattice QCD. If the quark-gluon plasma produced in these collisions is as hot as theoretically predicted, it will shine brightly, producing many thousands of energetic particles in a single collision.

Resolving and recording such complex events at the rate of hundreds per second poses an unprecedented challenge for detector technology, integrated circuit electronics development, and information handling, storage and processing technologies. The requirements for the two large RHIC detectors, STAR and PHENIX, exceed those encountered in any previous experiment and have triggered vigorous research and development efforts in instrumentation and data processing technology. The STAR detector, for example, will be able to make a complete analysis of all emitted charged particles permitting the determination of the temperature and the abundance of particle species for each single collision. The PHENIX detector will record the difficult to observe but critical processes by which photons and lepton pairs are radiated from the moment of quark-gluon plasma formation. These large detectors, along with several smaller and more specialized devices, will investigate signatures of the quark-gluon plasma, study its behavior in detail and be prepared for unexpected discoveries of new phenomena at high temperatures and densities.

III.B. Facilities, Instrumentation, and Technology

Experiments in nuclear physics bring to bear a broad range of facilities and technologies. The continuous advancement of these technologies, essential to maintaining world leadership in nuclear research, provides a rich milieu for training and innovation over a wide spectrum of technical areas, including electronics, vacuum techniques, large-scale data acquisition and computer systems with corresponding software development, novel detection systems and sensors, automated high-level control systems, ion-beam and accelerator technology, and superconductivity.

Because of the scale of the accelerators required for most research in nuclear science, the health and strength of the laboratory infrastructure is critical to the field. Here we briefly review this infrastructure and comment on its current status. We then provide examples of how knowledge and technology that have evolved from research in nuclear science are contributing to national needs in other areas. The broader study requested in the current charge (Appendix 1) will be pursued in the near future.

III.B.1. Infrastructure Requirements of the Field

It has been emphasized in each of the Long Range Plans for nuclear physics that the field has need for primary beams of electrons, protons, and heavy ions. Each serves a complementary class of experiments. Secondary beams of other particles such as neutrons, pions, muons, neutrinos and radioactive ions can be derived principally from intense proton beams. Accelerator facilities for nuclear science fall into two major categories: larger facilities that operate for substantial outside user communities, and smaller facilities that mainly serve local groups of scientists. In addition, high energy physics laboratories, reactors and other neutron sources, and specialized facilities such as solar neutrino detectors complement and extend our research capabilities.

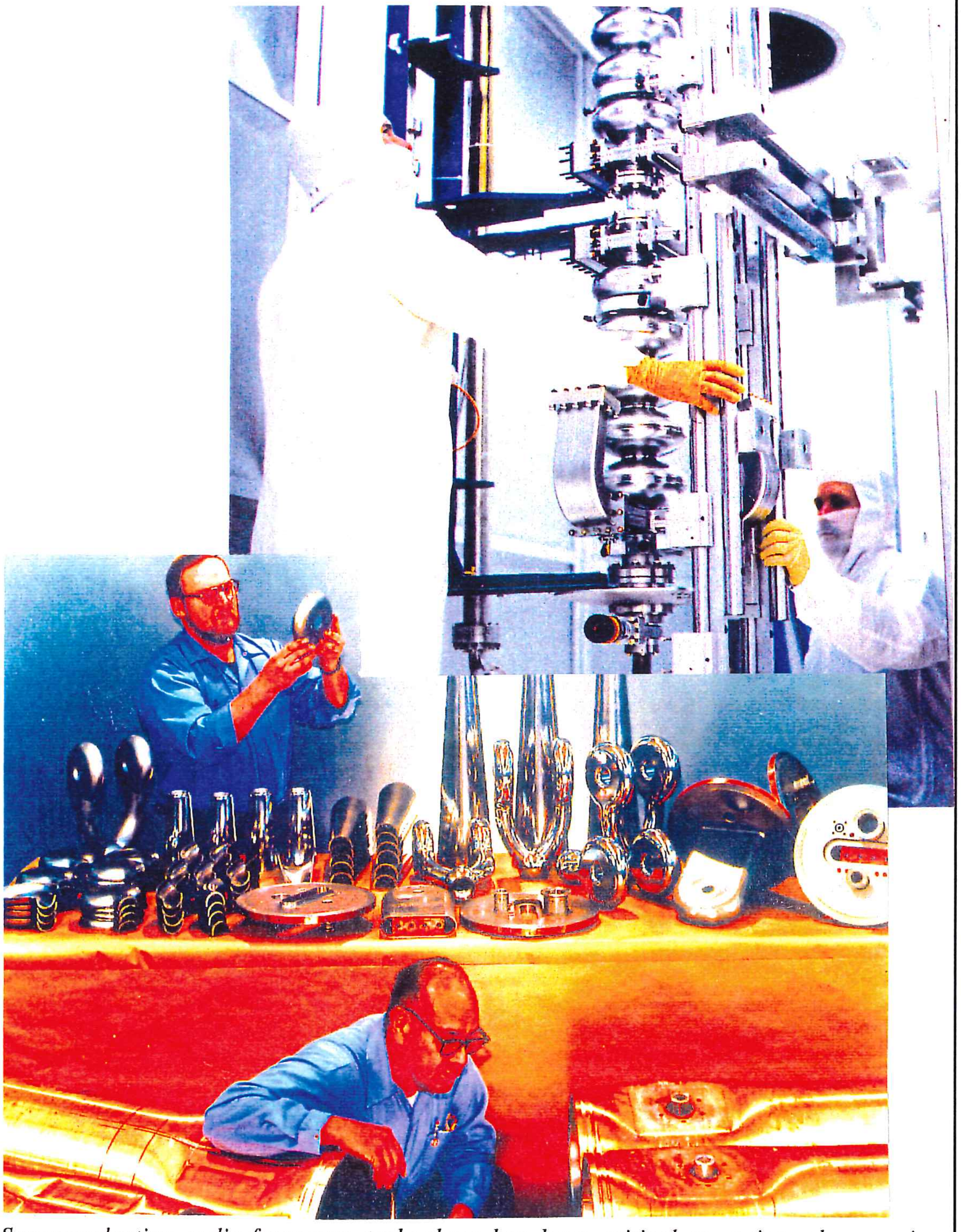
Electron Accelerators: The principal recommendation of each of the Long Range Plans developed for nuclear science involved the need for multiple, high-intensity multi-GeV electron beams having the continuous-wave (cw) time structure necessary for high-rate coincidence experiments. In response to these recommendations, construction of the Continuous Electron Beam Accelerator Facility (CEBAF) began in 1987. This facility will provide cw electron beams with energies between 0.5 and 4 GeV and currents up to 200 microamperes, divisible into three simultaneous beams serving three separate experimental halls. The three halls are being equipped with complementary forefront instrumentation including high-resolution coincidence capabilities and large-acceptance detectors for multi-particle final states. Polarized electron and photon beams will also be available. To achieve the high current cw beams, CEBAF has successfully undertaken the large-scale application of superconducting radio-frequency (rf) cavities operating at liquid helium temperatures, a major advance in accelerator technology.

Construction of the CEBAF accelerator is essentially complete, and commissioning activities are now under way. The research program at CEBAF is driven by a large and active user community: Over 450 scientists from 101 institutions and 17 countries are participating in approved experiments.

The Bates Linear Accelerator Center at MIT provides complementary capabilities at lower energies. The facility has set the standard for high resolution ($\geq 4 \times 10^{-5}$) electron scattering studies of nuclear structure. This low duty factor (1%) accelerator, which has been in operation for over two decades, recently was upgraded by the addition of the South Hall Ring (SHR). When commissioning of the ring has been completed, nearly continuous electron beams with energies up to 1 GeV and average currents up to 50 microamperes will be available. This will take advantage of special detectors now being brought into operation: out-of-plane spectrometers and a focal plane polarimeter for spin transfer experiments. These have been developed as joint DOE-NSF initiatives. In addition, internal target experiments can be carried out within the ring (operating in a storage mode) with circulating currents up to 80 milliamperes. This dedicated internal target facility provides unique opportunities for measuring spin observables and is a complement to extracted beam facilities such as CEBAF. The MIT group and the Bates user community have pioneered the use of spin observables in electron scattering.

The capabilities of these two nuclear physics electron accelerators are augmented by experiments carried out with higher energy electron beams obtained at SLAC, muon beams at Fermilab, and lepton beams at other high energy facilities abroad.

Proton Accelerators: The Los Alamos Meson Physics Facility (LAMPF), the premier nuclear physics facility in the United States for over two decades, provides beams of protons with currents up to one milliampere and energies up to 800 MeV, and generates secondary beams of pions, muons, neutrinos, and spallation products. LAMPF has supported a far-reaching program of both basic and applied research. For example, the neutron beams provided to the LANSCE and WNR facilities serve a large group of scientists studying materials and defense applications.



Superconducting radio-frequency technology has been critical to major advances in accelerator capabilities, and is showing promise for industrial applications. The top photo shows the two-cell, superconducting cavity pair developed for CEBAF, the continuous-wave electron accelerator nearing completion in Newport News, Va. The bottom photo shows component parts for the superconducting resonators developed for ATLAS, the heavy ion accelerator at Argonne National Laboratory.

Certain complementary capabilities are available from the high energy physics facilities at Fermilab and the Brookhaven AGS, and from the Indiana University Cyclotron Facility (IUCF), one of the two major accelerators operated by the NSF as national user facilities for nuclear science. IUCF can provide external beams of both polarized and unpolarized light ions with energies up to 210 Q^2/A MeV and stored, cooled beams with energies up to 560 Q^2/A MeV but no secondary beams. Nuclear physics experiments are carried out using hadron beams from Fermi Lab and the AGS, including their secondary beams.

The 1992 update of the Long Range Plan projected an orderly phaseout of the program at LAMPF through FY1995, necessitated by hard choices created by the tension of new opportunities and budgetary stringencies. This plan, supported in the FY1994 Appropriations language, took cognizance of several major experiments which need FY1995 operation to realize the science. The Long Range Plan also looked forward to U.S. participation in new initiatives in hadron physics such as the KAON facility at TRIUMF, which was under consideration at that time for funding by the Canadian government. With the subsequent cancellation of the KAON project, the closure of LAMPF will leave nuclear science with very

Aerial view of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The existing Tandem van de Graaf accelerators, Booster Accelerator and the Alternating Gradient Synchrotron (AGS) will accelerate heavy nuclei for injection into RHIC. After further acceleration, two counter-rotating beams will collide at energies of up to 100 GeV per nucleon. The RHIC accelerator (3.8 kilometers in circumference) and associated experiments are under construction and expected to be completed for operation in 1999.

limited opportunities to address important questions that can only be answered with the kinds of experiments that can be mounted at high-intensity, high energy hadron accelerators. Such accelerators are needed to generate intense secondary beams (mesons, neutrinos, muons) which uniquely open up major investigations. The next NSAC Long Range Plan will need to reconsider options to pursue this area of science.

Heavy Ion Accelerators: After pioneering experiments with near-relativistic heavy ion beams at the Berkeley Bevalac, a program which started twenty years ago and helped develop many of the firsts ideas underlying the science of hot, compressed nuclear matter, nuclear physicists began exploring the high density phase of nuclear matter with relativistic ion beams beginning in 1986. At that time ions of mass number near 30 (e.g. silicon and sulphur ions) were injected into the Brookhaven AGS and the CERN SPS, both of which have operated for many years as high energy proton accelerator facilities. At Brookhaven, an existing Tandem van de Graaff machine provides the ion source. In 1992 the completion of a dedicated booster pre-accelerator made possible the injection of the heaviest nuclei, up to a mass number of 200 (e.g., gold ions), in the AGS.

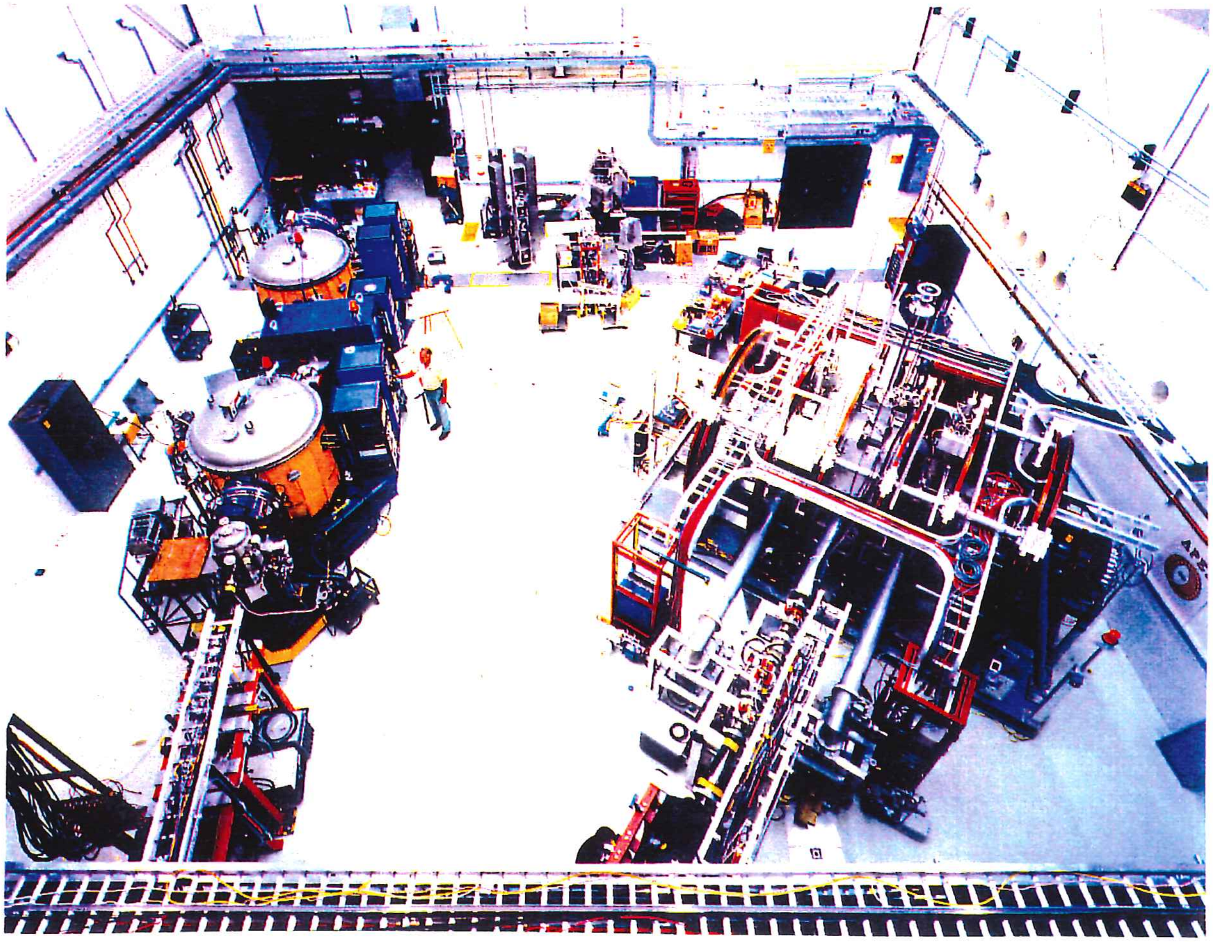
Beginning with its 1983 Long Range Plan, the nuclear physics community has identified as one of its highest priorities the implementation of a colliding beams facility capable of producing heavy ion collisions at energies of the order of hundreds of GeV per nucleon: more than ten times the energies achievable in the present, fixed-target facilities. This facility, the Relativistic Heavy Ion Collider (RHIC) is now under construction at Brookhaven. It will make use of the existing accelerating structures, including the AGS, for injection into a pair of superconducting magnet rings in a tunnel 3.8 kilometers in circumference, producing two counter-rotating Au beams, each with an energy of 100 GeV/c per nucleon. Large collaborations, involving a total of 670 scientists from 77 institutions and 15 countries, have formed to construct the detectors necessary to exploit the capabilities of this new facility. Research operations are expected to begin in 1999.

The nuclear structure and reaction studies described in Section III.A.1 must be carried out at lower energy heavy ion facilities. These include the K1200 superconducting cyclotron operated by NSF at Michigan State University, and the DOE-operated facilities ATLAS at Argonne National Laboratory, HRIBF at Oak Ridge National Laboratory, and the 88 Inch Cyclotron at Lawrence Berkeley Laboratory.

The Argonne Tandem Linac Accelerator System (ATLAS), based on novel low-frequency superconducting rf technology developed at Argonne, has completed a successful upgrade last year providing intense ion beams of highest quality up to uranium. About 200 users from more than 40 institutions, predominantly U.S. universities, are involved in an active research program. Forefront research is being pursued with novel instrumentation, including the ATLAS Positron Experiment (APEX) and the high-resolution Fragment Mass Analyzer (FMA). The combination of the beam capabilities of the accelerator and the special instrumentation provide for opportunities in heavy-ion research unique in the nation.

The Holifield Radioactive Ion Beam Facility (HRIBF), currently under construction, will be the first accelerator facility in the U.S. dedicated to providing high-intensity radioactive ion beams for fundamental research in nuclear physics and nuclear astrophysics. The combination of beam species, energies, and ions with an extensive complement of research apparatus will make the HRIBF a unique research facility. Among the new experimental devices to be available are a recoil mass separator, an enhanced velocity separator transferred from the U.K. Daresbury Laboratory, and an upgraded germanium detector array.

Gammasphere is a new detector system under construction at the 88-Inch Cyclotron at Lawrence Berkeley Laboratory at a total cost of $20M. When complete the detector will



The ATLAS Positron Experiment (APEX) (right) to study supercritical electromagnetic fields that exist for the short period during the collision of two heavy nuclei, and the Fragment Mass Analyzer (FMA) to study short-lived nuclei far-off stability at the Superconducting ATLAS Accelerator at Argonne National Laboratory.

comprise 110 germanium gamma ray spectrometers and will be the most powerful such system in the world. Gammasphere is currently in its early implementation phase with 35 detectors operational. In the past year, 30 experiments have been carried out involving 104 users from 31 universities and laboratories. In late FY1994 the number of operating detectors will be increased to 50, and the project will be complete in October 1995.

University Facilities: There are presently fourteen smaller accelerator facilities funded by DOE and NSF. They are situated on university campuses, and play a number of important roles. First, some forefront questions in areas such as nuclear structure, nuclear astrophysics, and fundamental aspects of beta decay can only be addressed using smaller, more flexible, specialized accelerators. Second, these laboratories have served as a hotbed for the development of interdisciplinary applications of nuclear technology; for example, AMS has been developed at low energy facilities. Third, these facilities provide on-campus research opportunities for graduate students, who can be given considerable responsibility and flexibility in their training. Finally, they serve as staging areas for groups that carry out part of their research at the larger laboratories, using local technical support for construction of apparatus and local beams to calibrate detectors.

III.B.2. Nuclear Physics and the National Interest

Research in nuclear science has resulted in important new technologies. Their development has depended critically on our understanding of nuclei and on advances in accelerators and radiation detectors resulting from the pursuit of nuclear science. These new technologies have contributed to the national interest in health, economic growth, environmental protection, and national security. Training in nuclear physics research generally leads to familiarity with the associated technologies and indeed often entails extending those technologies. In this section we provide some examples of direct relevance to societal goals.

Health: Nuclear physics has had dramatic impacts on medicine, providing important tools for biomedical research and for medical diagnosis and treatment. The field of nuclear medicine began with collaborative efforts between nuclear physicists and physicians. Today, 3500 hospital-based nuclear medicine departments in the US perform 10 million nuclear medicine procedures each year, generating about $1 billion in business.

Radioactive isotopes produced by accelerators are widely used in many areas of biological and biomedical research. By inserting such radioisotopes as carbon-14 and tritium (an isotope of hydrogen), it is possible to turn molecules into tiny transmitters without perturbing their natural biological properties. The signals from these transmitters (their unique radioactive decays) tell researchers how molecules move through the body, what types of cells contain receptors, and what kinds of compounds bind to these receptors. Radioisotopes help researchers to develop diagnostic procedures and to create new pharmaceutical treatments for diseases, including cancer, AIDS, and Alzheimer's disease. Radioactive tracers are also indispensable tools for the new forensic technique of DNA fingerprinting, and for the Human Genome Project, which seeks to unravel the human genetic code.

Procedures that use accelerators directly are becoming increasingly important as research and diagnostic tools in medicine. For example, the new technique of accelerator mass spectrometry (AMS) has dramatically improved the sensitivity of radioisotope concentration measurements over conventional techniques because it isolates the isotopes directly, rather than measuring their decay products. In principle, AMS can find any isotope of any element in concentrations well below one part per trillion. This sensitivity permits measurements of the biomedical effects of chemicals and pollutants in the environment at realistic exposure levels, unlike conventional techniques which require artificially high levels of exposure to see any effect. Other research in progress is aimed at using AMS and related techniques, to determine the optimal dose of a pharmaceutical for each individual on the basis of his or her unique biochemical response.

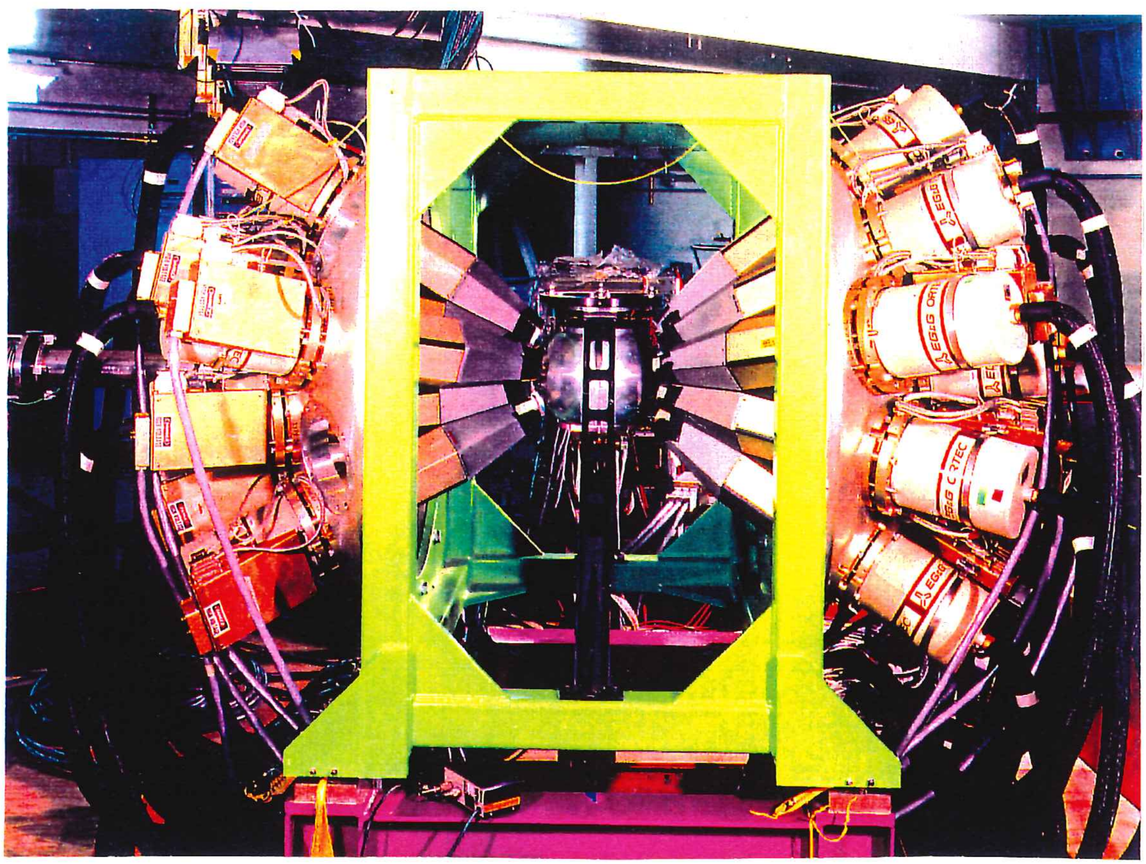
Advanced nuclear diagnostic techniques such as proton radiography and tomography and positron emission tomography (PET) have revolutionized medicine by providing ways to "see" inside the body without surgery. The practitioners are often nuclear physicists who work with physicians to develop and apply the techniques.

Gamma radiation has been used as a treatment for cancer for many years. The gamma-rays are generated by microwave linear accelerators originally developed for nuclear physics research; the versions optimized for medical treatment grew out of collaborations between nuclear physicists and radiologists. Unfortunately, gamma-rays deposit most of their energy where they enter the body, then successively less until they exit. As a result, normal tissues receive higher doses of radiation than the tumor. Thus, although the clinical benefits of this radiation treatment have been considerable, radiologists would prefer alternate approaches which could better localize the dose.

These considerations have led to substantial research on radiation therapy using fast neutrons, boron neutron capture, heavy ions, and protons. Proton therapy, in particular, is evolving rapidly as a highly promising alternative treatment for a number of specific cancers. Unlike gamma-rays, protons (and heavy-ions) deposit most of their energy at the end of their range. As a result, radiologists can increase the dose to the tumor while reducing the dose to normal tissue. By using multiple proton beams, it is possible to concentrate virtually all of the radiation on the region of the tumor while minimizing the dose received by healthy tissue. Proton therapy is now the preferred treatment for cancers of the eye and cancers near the spinal cord.

The Economy: Nuclear science makes many direct contributions to the economy. Even in the absence of new U.S. initiatives in nuclear power, nuclear science is developing important diagnostic tools, such as neutron diffraction radiography, for improving the safety of operating reactors. Nuclear physics research will also help solve the problems associated with disposal of radioactive waste in a world that obtains one sixth of its electricity from nuclear power.

Nuclear technology is also important for fossil fuel power generation. Nuclear instruments are used as basic tools to identify geological features in the drilling of oil and gas wells. Nuclear techniques are used routinely to reduce environmental pollution from coal-powered electrical plants by monitoring the chemical composition of the coal to be burned (e.g.,



GAMMASPHERE, the high-resolution gamma-ray detector system for nuclear structure research of rapidly rotating nuclei. The facility is currently under construction at Lawrence Berkeley Laboratory. Each "arm" consists of a germanium detector with bismuth germanate scintillator shield. 25 of the 110 spectrometers are installed and operating.

the sulfur content). About 500 on-line analyzers have been installed by the electric utility industry; the most sophisticated of these use the nuclear technique of prompt gamma neutron activation analysis. These analyzers can be used to monitor the quality of coal at the mine, to sort and blend it, to monitor and control the operation of coal preparation plants, to determine the commercial value of coal, to enforce coal contracts, and to streamline the operation of power plants.

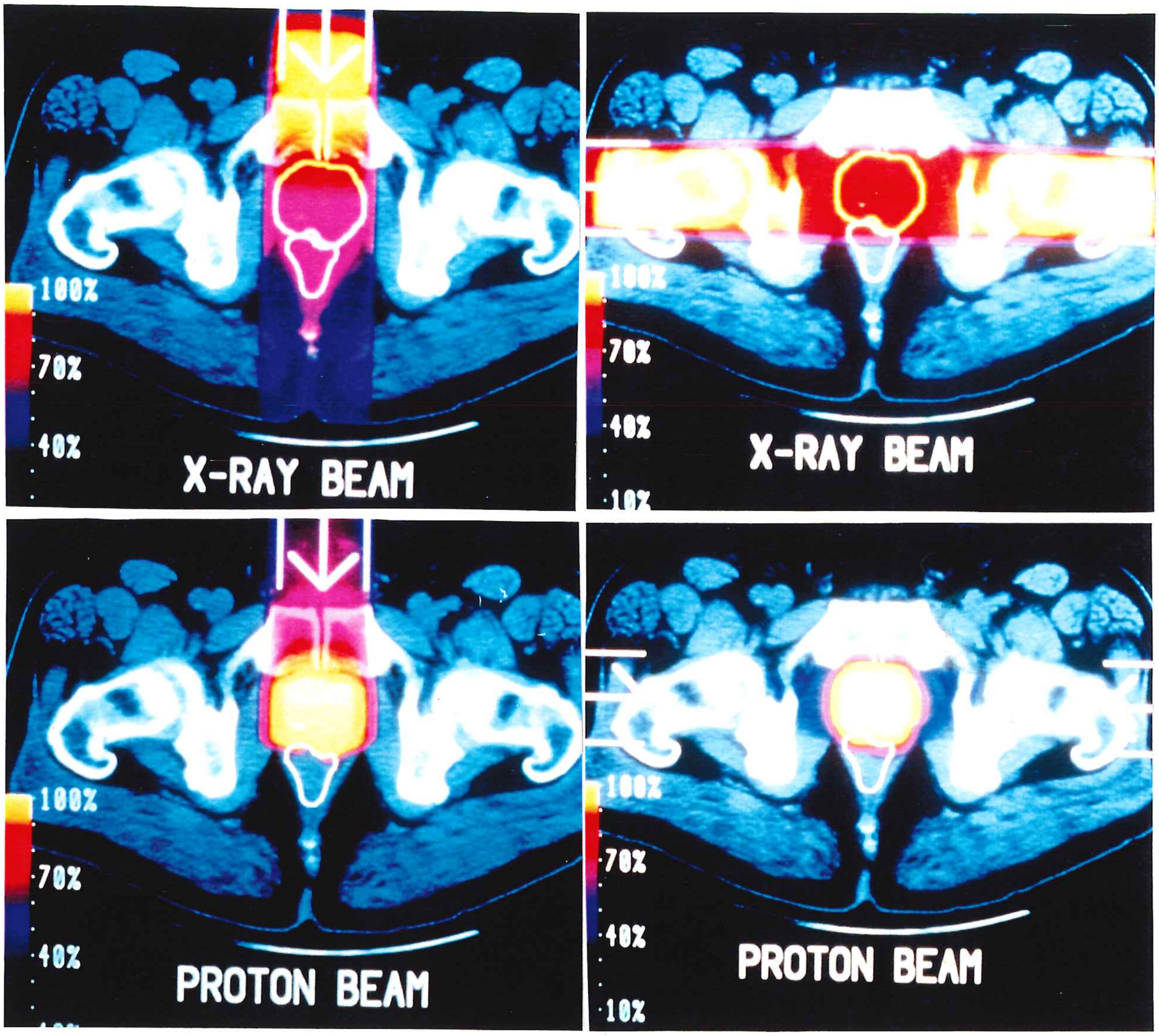
Nuclear fusion, the process by which the sun generates energy, has the potential to offer many advantages for power generation. DOE has established a goal to operate a demonstration fusion power plant in the year 2025. Low-energy accelerators that have evolved from nuclear science are used in the fusion power program, both for producing the beams of neutral particles used to heat the plasma and for producing intense neutron beams used to test materials used for fusion reactors.

Nuclear technology is widely used in the electronics industry. Based on accelerator concepts originally developed by nuclear (and high-energy) physics for fundamental research, beams of fast and slow neutrons and light from synchrotron sources are basic tools for the characterization of condensed matter systems. Nuclear technology is also used routinely on the factory floor. For example, ion implantation, which uses accelerators that are direct descendants of machines developed for nuclear physics, is the basis for manufacturing integrated circuits. It replaced diffusion as the dominant doping technique as integrated circuits evolved to smaller and smaller features because it offers more precise control. All VLSI (very large scale integration) circuits manufactured today are ion implanted. The nuclear technologies of Rutherford back scattering and channeling are important quality assurance techniques in the semiconductor industry, for measuring the effectiveness of production procedures.

Another promising accelerator application is ion beam lithography, the technique of choice for the fabrication of integrated circuits using high-temperature superconductors. A shift register made of yttrium barium copper oxide using this technique recently operated at 120 gigahertz, the fastest speed yet achieved for a complex integrated circuit.

Nuclear technology also finds many applications in non-destructive testing. Just as medical imaging shows the interior of the human body without surgery, industrial imaging using nuclear techniques and detectors shows the interior of equipment without disassembly. For example, neutron radiography permits the sensitive detection of potentially dangerous corrosion inside an airplane wing without the need to disassemble it. Gamma-ray tomography is used to image piping in the electric power industry, processing lines in the chemical industry, and tubular products manufactured in steel mills.

A recent development that may have profound industrial impact is the superconducting radio-frequency electron accelerator, just brought to maturity in the U.S. for nuclear physics research at CEBAF. It offers the potential as a driver accelerator for a new kind of industrial light source: the high-average-power, wavelength-tunable free electron laser (FEL). FELs circumvent the two main limitations of conventional lasers: they can produce monochromatic light over a broad range of wavelengths, spanning the infrared, visible and ultraviolet (UV); and they can produce extraordinarily high power levels because they are not restricted by heat generation in the "lasing" medium. Industrial interest is growing worldwide for the potential applications of FELs, which include advanced materials, materials processing, manufacturing, pollution remediation, medical imaging, textiles, adhesives, and diagnostics. Intense light at the appropriate wavelength has a demonstrated ability to alter the chemistry, topography, and morphology of materials, surfaces, and interfaces. The key to the commercial viability of these processes is low-cost UV light; FELs have the promise of achieving this by reducing the cost of UV light by a factor of 100 relative to available sources. In many applications replacement of a



A new cancer treatment has been developed which uses ion beams (for example protons) from accelerators similar to the ones originally developed for nuclear physics research. X-rays, the conventional treatment for cancer, deposit most of their energy where they enter the body, then successively less until they exit. As a result, normal tissues receive higher doses of radiation than the tumor. Protons penetrate tissue only to a controllable depth and deposit most of their energy at the end of their range. As a result, radiologists can increase the dose to the tumor while reducing the dose to normal tissues. The four images compare X-ray beams and proton beams in their ability to localize dosage. A tumor of the prostate gland appears in the center of each image. The colors indicate how the energy deposited in the tissue varies with position--yellow is the maximum energy, followed by red, orange, and purple.

wet-chemistry process with one driven by an FEL will also provide a substantial environmental benefit.

The Environment: Nuclear science is making fundamental contributions to our understanding of the environment we live in by providing highly sensitive diagnostic and research tools. In addition, accelerator technology has found application in environmental protection and remediation, providing techniques for purifying waste water, utility stack gasses, and toxic waste.

The dramatically increased sensitivity of AMS has revolutionized carbon-14 dating and provided scientists with an important new tool for solving problems related to global warming, air and water quality, and stratospheric ozone depletion. For example, it is now possible to use carbon-14 dating to understand oceanic circulation patterns and their influence on weather. The atmosphere exchanges carbon dioxide (CO_2) with the ocean, which tends to inhale CO_2 near the poles and to exhale it near the equator. As the water ages, the carbon-14 content of its CO_2 decreases. AMS studies of thousands of seawater samples taken at various longitudes, latitudes, and depths are allowing researchers to create a 3-D map of the age of the oceans and infer circulation patterns. This 3-D map is also providing insights into the phenomenon of global warming by teaching us about CO_2 exchange between the atmosphere and the oceans; an understanding of this cycle and its natural fluctuations will help scientists understand the significance of man-made CO_2 in the atmosphere.

AMS can also provide valuable information about groundwater resources by determining the age and recharge rates for aquifers from their carbon-14 content. AMS studies of the particulates in smog can specify the relative contributions of wood burning and fossil fuel burning since wood contains carbon-14 and fossil fuels do not. AMS studies of such radioisotopes as beryllium-7 and beryllium-10 are helping to clarify the basic science underlying stratospheric ozone depletion by providing information on the mechanisms of exchange between the stratosphere (the upper atmosphere) and the troposphere (the lower atmosphere). These studies also permit scientists to trace aerosol movement in the upper atmosphere; this information is important because aerosol particles serve as host sites for chemical reactions which create the forms of chlorine that destroy ozone.

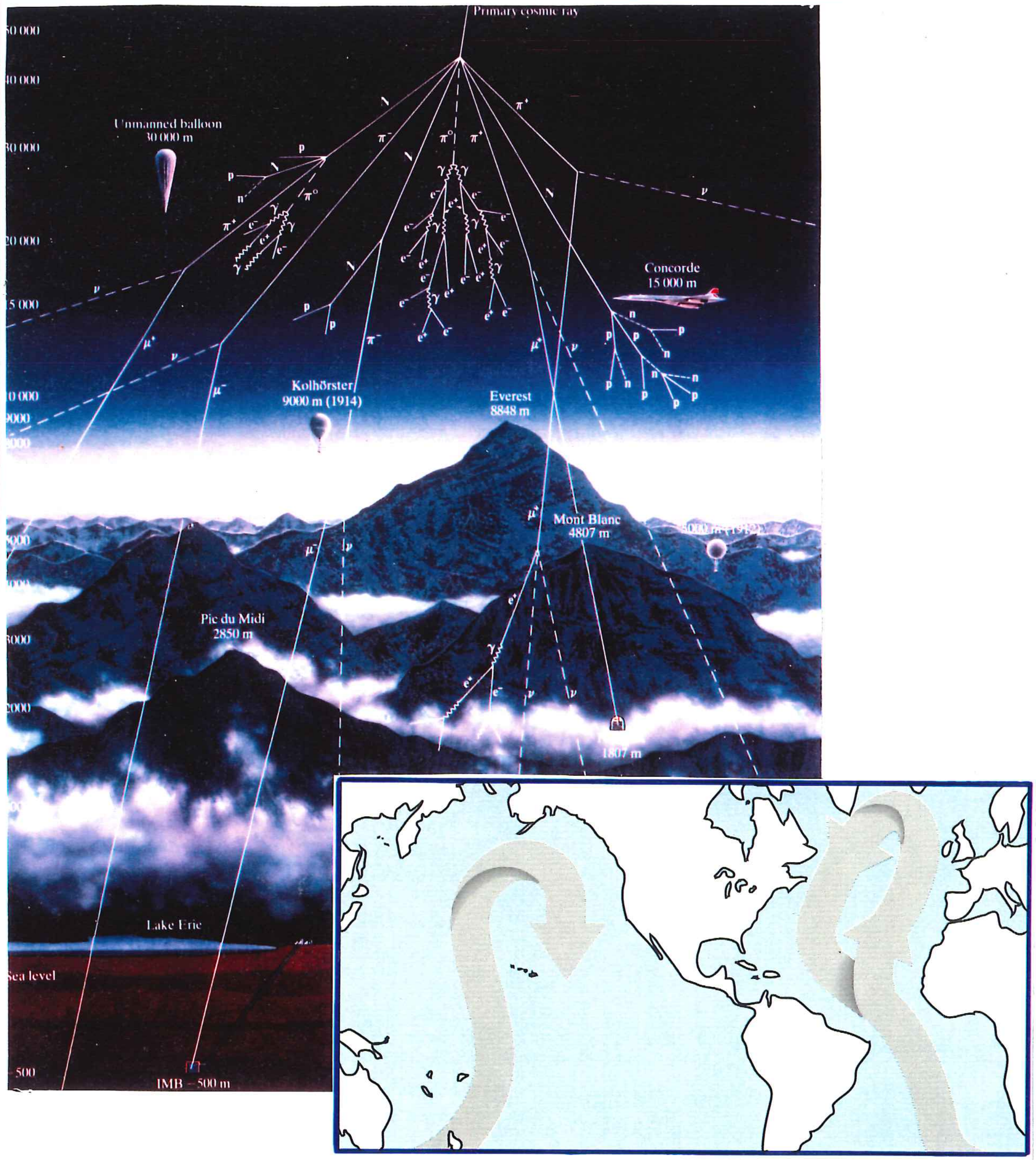
Proton-induced gamma-ray emission (PIXE), a nuclear physics technique used for studies of air pollution, enables the researchers to determine the constituents of haze in concentrations below 1 part per trillion, often permitting the identification of the source of the pollution.

National Security: Nuclear defense has been a critical aspect of our lives for half a century. As we enter a new era, nuclear science continues to make important contributions to our nation's security through disarmament, including the dismantlement of nuclear weapons, the verification and identification of chemical weapons, and environmental remediation. Moreover, in the absence of ongoing testing of nuclear weapons, nuclear physics techniques will be increasingly important in maintaining the viability of the weapons that remain in our stockpile.

DOE is scheduled to disassemble 1000 to 2000 nuclear weapons per year for the next five years. The time required to disassemble a nuclear weapon ranges from a few days to a few weeks, depending on the type of weapon. Engineers dismantle the weapons; physicists help design the protocols and provide consultation when questions arise.

Many sites at which nuclear weapons were fabricated now suffer from soil contamination. Physicists have developed a portable soil analysis system that employs detectors from nuclear physics experiments to measure radioactive decay from trace amounts of plutonium. This system makes it possible to adhere to strict standards of soil purity during cleanup.

The United States and former Soviet Union countries have also agreed to diminish their stockpiles of chemical weapons. Since warheads containing chemical weapons and



Cosmic-ray induced nuclear reactions in the atmosphere and the earth's crust generate long-lived radioisotopes that serve as wide-spread tracers and dating tools in various studies of geophysical and environmental importance. It is now possible, for example, to use accelerator mass spectrometry (AMS), a technique that was recently developed at nuclear physics accelerators, for highly sensitive carbon-14 dating to measure the age distribution of carbon-dioxide dissolved in oceanwater. This provides important information for understanding oceanic circulation patterns and their influence on the weather, and insights into the phenomenon of global warming.

conventional weapons often look alike, treaty verification procedures require a method of distinguishing between them without drilling a hole in the casing. Nuclear physicists have developed a portable system for making this distinction, identifying the elements by their gamma-ray signatures.

Nuclear technology is also providing important new security tools for the detection of narcotics and explosives. Systems based on the nuclear technique of thermal neutron analysis can find narcotics and explosives inside luggage, vehicles, and containers. This technique bathes the luggage in low-energy neutrons, then analyzes the gamma-rays coming from the nuclei inside. This provides specificity in identifying elements of interest, such as nitrogen, in contrast to the currently widespread use of x-rays. A more sophisticated system, known as pulsed fast neutron analysis, is under development; it uses detectors and computers to produce a high-resolution, 3-D picture of the inspected volume.

III.C. Education and Human Resources

Nuclear physics is a significant contributor to DOE's commitment to improving the scientific and technological education of Americans. The nuclear physics program produces a large number of young scientists who help sustain American leadership in basic science and who possess knowledge and skills of broad importance to society. The nuclear physics community has also taken responsibility for helping to diversify the technological and engineering workforce and to increase public literacy in science over the long term.

III.C.1. Graduate Education and Employment

Nuclear physics seeks the fundamental understanding of strongly interacting matter and of the forces that govern its behavior. New ideas, detectors, and facilities provide new opportunities and challenges. These efforts ultimately determine the success of the associated educational mission in attracting and training high-quality young scientists.

In FY1993 the DOE nuclear physics program directly supported 426 graduate students and 101 Ph.D.'s were awarded. The NSF's university-based nuclear physics program supported 373 graduate students; many of these students depend on DOE-supported user facilities for their doctoral research opportunities. Approximately 1,300 physics Ph.D.'s are awarded annually in the United States. Thus, the DOE nuclear physics program was directly responsible for about 8% of the total physics Ph.D. production in FY1993, and the research supported through its facility operations brings this share to well over 10%.

The majority of the graduate students in the program rely upon stable DOE planning and funding for the program, including the operation of existing facilities and the timely completion of new facilities and detectors. Fluctuations and sudden shifts are devastating for the development of this important human resource. The subsequent employment of these young people is clearly of considerable concern to the nation. The short time available to the subcommittee has not permitted a systematic study of these issues. Nevertheless, our preliminary investigation reveals that employment prospects for nuclear physics Ph.D.'s remain strong. As in other fields, permanent positions in basic research in academia, national laboratories, and industry are available for some of the graduates, while most enter the workforce in a great variety of enterprises. The diversity in the employment opportunities for nuclear physics graduates is neither new nor undesirable. Indeed, the field has a long tradition of producing a highly-educated and flexible group of scientists with the broad knowledge and skills essential to assume leadership in fulfilling society's science and technology needs.

Within the research enterprise itself, despite pressures on academia, many young people enter the field as principal investigators. They will provide innovation and fresh leadership for the decades ahead. The nuclear physics program has been quite successful in developing new academic research positions throughout most of the nation. One particularly notable success resulted from the great expansion of activity in the Southeast stimulated by the construction of CEBAF. Sixty-two new, CEBAF-related tenured or tenure-track positions have been created and filled in the Southeast since 1982 in nuclear physics and accelerator technology, and searches are in progress for fourteen more.

Nuclear physics has made many contributions to the national interest including: accelerator and detector technology, which has been advanced largely by nuclear and high energy physicists; sophisticated computer programming; the application of radioisotopes in medical diagnostics and therapy; and the development of new state-of-the-art instrumentation for medical research. Accelerator technology is also crucial to DOE's role in materials research and the many industrial developments. DOE's national security responsibilities, including stockpile stewardship, will be even more science-based in the new security environment. The nuclear physics program, through its pursuit of forefront science, is producing well-trained young scientists who find high-quality jobs in the nation's R&D enterprise. It is producing young scientists who are central to maintaining DOE's core competencies.

III.C.2. Diversity and Scientific Literacy

Sustained excellence of the American scientific enterprise in the decades ahead will require that we fully utilize our human resources and that we have the support of a scientifically and technically literate public. The nuclear physics community, supported by DOE and NSF, contributes to these areas as a basic element of its research program. Numerous laboratories and university research groups are involved in grassroots efforts to attract under-represented minority students into science and to contribute enrichment and training for K-12 science teachers. Other groups are working on museum displays and public activities aimed at raising the scientific curiosity of the public-at-large.

Efforts are made at all DOE national laboratories to attract minority students into science. For example, at Argonne National Laboratory nuclear physics funds support an active recruiting program at historically black Colleges and Universities (HBCUs) which has generated strong minority participation in the laboratory's undergraduate summer science programs. Recently this has been extended to include a faculty leave program for HBCU staff which is expected to intensify these contacts.

The efforts at CEBAF provide another good example. As already noted, the Southeast has seen a significant growth in faculty positions in preparation for the new scientific opportunities offered by the facility. A substantial number of these have been created in HBCUs and minority educational institutions (MEIs). For example, Hampton University has added seven new faculty in nuclear physics and initiated a Ph.D. program in physics as a result. Furthermore, faculty at Hampton, together with support from MIT and the CEBAF management, have initiated a dual mentoring program for promising minority undergraduates. Norfolk State University, another HBCU, and Florida International University, a predominantly Hispanic MEI, are also adding faculty positions.

Another successful program, called BEAMS, brings the excitement of science to grade school children. In partnership with local schools and the commonwealth of Virginia, entire classes are brought to the facility for a full week of immersion in the scientific environment and exposure to diverse scientific and technical career role models. The program also uses the laboratory's resources to motivate teachers and involve parents. To date, about 10,000 students have benefited from the program. These programs exemplify the potential of nuclear physics assets, in partnership with local schools and colleges, to invest back in society.

Students experiencing the excitement of science through participation in the BEAMS program at CEBAF. Activities include hands-on experiments aimed at developing an understanding of how scattering can be used to infer the shapes of objects too small to see (left) and "magnet racing", which provides insights into how an accelerator works (right).

IV. BUDGETS AND PRIORITIES

The proposed reductions in DOE nuclear physics funding in the FY1995 Administration request (-14%), if implemented, threaten the continuing vitality of the field and its contribution to the DOE Science and Technology mission. The last NSAC planning activity was in response to the 1992 charge which sought advice under three different budget scenarios. The lowest of these was a constant as-spent dollar scenario of $363M (implying losses each year in real spending power). Subsequently, the FY1993 and FY1994 DOE nuclear physics appropriations of $355M and $349M, respectively, fell somewhat short of the minimum planning level. Although these funding levels necessitated a variety of stretchouts and cutbacks, reasonable progress has been realized towards the research and educational goals of the nuclear physics program discussed in Chapter III.

The FY1995 Administration request of $301M would represent a significant departure from the planning level. This precipitous reduction must lead to substantial inefficiencies in realizing the carefully structured investments made in nuclear physics over many years, to a major loss of high priority science, and to a significant reduction of professional positions and graduate student support across the nation. Continuation of funding at such a level will jeopardize America's world leadership in this important area of science. In this chapter we evaluate the proposed FY1995 nuclear physics budget against the needs of the program as planned by the agencies and the community.

Table 1 lists the FY1994 appropriations and the FY1995 Administration request. The third and fourth columns in the table list the base funds for FY1995 and FY1996 considered necessary by this Committee to meet the needs of the field for delivering the anticipated scientific, technical, and educational returns. The funds are grouped into four categories: (i) Research (approximately 50% at the universities); (ii) Facilities Operations at DOE National Laboratories; (iii) Capital Equipment (including AIP and GPP); and (iv) New Facilities construction (CEBAF and RHIC; with the transition from construction to research operation for CEBAF).

Table 1: DOE Nuclear Physics Funding (in M$) for FY1994, the Administration request for FY1995, and the funding recommended by NSAC in this Report

	FY1994 Appropriations	FY1995 Administration Request	NSAC Recommendation FY1995	NSAC Recommendation FY1996
<u>Research and Operations</u>:	211	180	213	204
Research[1]	112	113	118	124
Laboratory Operations	60	32	60	39
Equipment	39	35	35	41
<u>New Facilities Construction and Operations</u>	138	121	140	144
CEBAF[2]	60	51	60	64
RHIC[3]	78	70	80	80
TOTAL	349	301	353	348

[1]Approximately 50% at universities (including smaller facilities operation at universities).
[2]Contains $17M construction funds in FY1994 and $1M in FY1995; the funds recommended by NSAC for FY1996 are operating costs based on a recent SURA review of CEBAF operation and consistent with the 1992 NSAC Review (including AIP, GPP, and base equipment but not capital equipment funds for instrumentation upgrades or for completion of the CLAS detector).
[3]RHIC construction funds.

The FY1994 appropriation, although somewhat lower (-2%) than in FY1993, permits a reasonable research program. This is illustrated by the hours of research operation listed in Table 2 for the DOE-supported national facilities. The low energy heavy-ion facilities, ATLAS and 88" Cyclotron, are able to operate for a healthy fraction of their maximum utilization, but other facilities (AGS, Bates, and LAMPF) operate only one third to one half of their desired schedule. Nevertheless, important programs can be realized against the research goals outlined in the NSAC Long Range Plans.

Table 2: Beam hours for research at DOE user facilities for FY1994, for FY1995 based on the Administration budget request and for the present NSAC budget recommendation.

	FY1994 Appropriations	FY1995 Administration Request	NSAC FY1995	NSAC FY1996
CEBAF				
Commissioning	2000	1500	1500	-
Research	-	0	2500	4500
Bates (MIT)	2000	1000	2000	3000
AGS (BNL)	700	500	1500	1500
LAMPF (LANL)	2200	0	2200	0
ATLAS (ANL)	5000	4500	5000	5000
88" Cyclotron (LBL)	5360	4700	5360	5360
HRIBF (ORNL)	-	500	1000	3000

The FY1995 budget request, if implemented, will have severe consequences for the field. The most drastic impact would be on facilities operation, and specifically the research hours available at these facilities (Table 2). This applies to the existing facilities included in Laboratory Operations in Table 1, university facilities included under Research, and the new CEBAF, which is near completion. The consequences of the proposed FY1995 budget are detailed in the subsequent discussion. We also discuss the additional allocations recommended in this Report for FY1995 and FY1996, and the accompanying benefits:

- CEBAF will not be able to start operation in FY1995 of its high-priority research program concerning the role of quarks and gluons in nuclei. Funding will be sufficient to cover only the 10 weeks of operation needed for commissioning of this new facility. Research utilization of this premier new facility, with a total project cost (TPC) of about $550M, will be delayed until FY1996. A large user community, with many graduate students, has invested great effort in developing experimental equipment matched to the CEBAF research program.

  NSAC recommends that $8.9M be added in FY1995 to allow the first nuclear physics experiments at CEBAF and to preserve the staff levels needed for operation of this high priority new facility, with an additional $4M for full research operation of CEBAF in FY1996.

- LAMPF will be phased out prematurely as a nuclear physics facility in the FY1995 request (and the potential use of this facility by other DOE programs will be jeopardized.) Important science will be lost. As part of an orderly phaseout outlined in the 1992 NSAC Report, the program has been sharply-focused on the highest priority experiments (parity and time reversal violation in neutron capture; neutrino scattering and oscillations; search for muon to electron radiative transition; high-resolution studies with neutral pions). If the last year of planned operation is not realized, we will see severely diminished returns on the large investments made in developing these unique experiments.

  We recommend an additional $24M in FY1995 for the operation of LAMPF to complete the very important experiments involving hundreds of scientists and graduate students. This would end LAMPF operation as a nuclear physics user facility in an orderly fashion, with phaseout in FY1996, as projected by NSAC and by the Congress in the FY1994 appropriation bill.

- RHIC completion was stretched out from FY1997 to FY1999 because of budget limitations. In addition to delaying the science, the stretchout is adding $82M to the total project cost. The $78M appropriated by Congress for FY1994 allowed BNL to execute a crucial industrial contract (superconducting magnet construction) thus preventing additional delays and costs. The proposed FY1995 cut to $70M would place serious restrictions on timely completion of the large detectors and other machine components. The proposed increase in RHIC construction funds to $80M in FY1995 and FY1996, will bring RHIC construction closer to the levels of the original profile. It will thus help defray some of the additional project cost, and most importantly will ensure timely completion and immediate research use of the large detectors at the time when RHIC accelerator construction will be completed.

- The recently completed storage ring capability developed at the MIT-Bates Laboratory will see very limited operation with the FY1995 request. New experimental programs involving internal targets and spin degrees of freedom, using special detectors and targets developed by a large university community, will be delayed. Similarly, smaller university facilities (Seattle, Texas A&M, TUNL, Yale) will be forced to limit their research program. The university based facilities are very effective in combining education with innovative research at lower energies. One example of an opportunity that deserves support is the application of ion and atom traps for high precision measurements testing fundamental symmetries.

  We recommend adding $1.5M in FY1995 and FY1996 to more than double the utilization of the novel accelerator and detector capabilities at Bates. We also request $3.5M for university research groups to pursue new physics and to avoid the loss of about 40 graduate students in FY1995. For FY1996, we recommend a Research budget of $2M over the 3% cost of living increase to maximize research at the operating and new facilities, and partly to pursue science questions that can no longer be addressed at LAMPF after its phase-out.

- The development of 11 GeV/nucleon gold beams at the Brookhaven AGS and associated new experimental equipment has opened up important opportunities to study hot compressed nuclear matter. Initial results are intriguing, giving hints of new physics of matter under extreme conditions. Only 500 hours of research operation would be possible with the proposed FY1995 budget, severely restricting the development of this field which complements the future RHIC investigations.

  NSAC recommends adding $2M in FY1995 and in FY1996 to advance the Brookhaven relativistic heavy ion program, increasing several-fold the unique research opportunities with gold beams at the AGS.

- The smaller user facilities at DOE National Laboratories (ATLAS at ANL, 88" Cyclotron at LBL, HRIBF at ORNL) have recently developed new forefront capabilities for nuclear-structure research. The reduction in beam time will impact the use of Gammasphere, the premier nuclear structure facility for gamma ray detection just being brought into operation at Berkeley, and limit the unique studies of nuclei far-off-stability with the Fragment Mass Analyzer at Argonne. For the new radioactive ion beam capability at Oak Ridge, funding will only permit half of the commissioning time that is needed for start-up of this facility.

We recommend adding $2M for FY1995 and FY1996 to expand operations at the low energy accelerators with these new forefront capabilities.

- A large fraction of the research and operations budget is taken up by salaries and associated personnel costs. The total funding in Table 1 for Research, Laboratory Operations and CEBAF (which is now in transition towards operations) is $232M for FY1994 and $196M for FY1995. The precipitous reduction proposed for FY1995 would inevitably lead to a substantial manpower reduction, estimated at about 10% in FY1995 alone. Clearly, this reduced budget and its concomitant major reduction in research opportunity will also strongly and adversely affect graduate student training. The NSAC recommendation for the total for Research, Laboratory Operations, and CEBAF is $238M for FY1995 and $227M for FY1996. The latter is somewhat below the FY1994 Appropriation, reflecting the balance among many factors, such as phaseout of LAMPF, full operation at CEBAF, and strong university programs.

- Closely tied to the research efforts is the funding for new equipment and novel experimental instrumentation. The request for FY1995 equipment funds falls well below that for FY1994 (-10%). The availability of equipment funds has been chronically low, and the Administration request for FY1995 compounds this shortcoming. Many important projects involving new detectors or upgrades have been delayed or stretched out, leading to great inefficiencies in major initiatives. For example, implementation of ^{3}He proportional counters in the SNO project has not yet been funded so that only incomplete information on the crucial neutral current channels will be available from this detector in its initial configuration. The completion of the Gammasphere project was delayed in FY1993 and FY1994; experiments to date have used only a fraction of the powerful capabilities of this instrument. Exploitation of the unique capabilities of the Bates South Hall Ring (SHR) requires a large acceptance detector system coupled with polarized internal gas targets (BLAST); while the SHR and polarized targets are now available, the detector needed to maximize their use awaits funding. At CEBAF, many equipment items have been delayed or "de-scoped" due to inadequate funds; most notably, the Large Acceptance Detector will not be ready until at least two years after the beam turns on.

  The funding for equipment has been inadequate to utilize the capabilities of new and existing facilities properly. These delays and deferred projects are extremely disruptive to the careers of young researchers who establish new research directions for the field by proposing novel and innovative instrumentation. Such projects are also very important in educating large numbers of talented students. The Committee estimates that $41M in FY1996, a modest increase over the FY1994 amount, will greatly leverage the nuclear physics investment.

In proposing the planning numbers in columns 3 and 4 in Table 1, the Committee places *highest priority* on carrying out the research program, using new and existing DOE facilities. This includes sustaining strong university programs (both DOE- and NSF-supported), the effective utilization of operating facilities and of CEBAF by providing the necessary beam hours for research (Table 2), and sustaining the necessary scientific manpower and student training.

High priority is attached to timely realization of new opportunities through ongoing facility construction and new equipment development. Most important, increased funding of RHIC construction more closely reflects the original project plan, thereby reducing total construction costs. This will ensure effective exploration of the new scientific frontier opened to study at

RHIC. Adequate support for innovative equipment projects at universities and new facilities are needed to increase the scientific return on our investments.

It is important to note that the present funding scenario discussed by this Committee precludes any other new facility initiatives, as originally contained in the 1992 Implementation Plan. The research opportunities with high-energy intense hadron beams that were to be provided by KAON are now lost with the demise of this Canadian project. The interest in this research remains high as evidenced by a large research community that has organized several workshops on the science in recent years. A next-generation facility for radioactive beams has been endorsed by a significant number of scientists and discussed at various workshops organized by that community. These and other significant initiatives, discussed in the Long Range Plan, retain their scientific validity, but the current budgetary climate clearly precludes NSAC endorsement of any major new project at this time. Major new initiatives will have to be taken up in the next NSAC long range planning activity with input from the broader nuclear physics community and the agencies.

V. CONCLUDING REMARKS

The NSAC assessment and recommendations presented in this report are based on five key elements:

- **Scientific return on the nation's investment:**

  The quality of the science is very high, a judgment based ultimately on peer review. The American nuclear physics program is clearly in the leadership position.

  The scientific opportunities to be realized in the next years are entirely consistent with established Long Range Plan priorities.

  Effective utilization of facilities and detectors for the highest quality science is a central issue in realizing a satisfactory scientific return on the nation's investment. Thus, for the DOE nuclear physics user facilities, our recommendations incorporate the following:

  - LAMPF operation in FY1995 and phaseout as a nuclear physics user facility in FY1996; this follows NSAC recommendations, is consistent with FY1994 appropriations language, and preserves options for other DOE programs that might use the LAMPF high intensity accelerator.
  - CEBAF should start research in FY1995 and move into full operating mode in FY1996.
  - The smaller user programs should exploit their novel capabilities for forefront research:

    ANL/ATLAS: FMA and APEX
    BNL/AGS: Relativistic heavy ion collisions with Au beams
    LBL/88" Cyclotron: Gammasphere
    MIT/Bates: South Hall Ring, spin capabilities and SAMPLE
    ORNL/HRIBF: Radioactive ion beams

- **Timely and cost-effective realization of major new scientific opportunities under development:**

  The RHIC project needs to be advanced for both scientific reasons and cost-effectiveness. In particular, the detector complement should be kept on track to be as robust as possible when the colliding beams are available.

- **Appropriate scientific manpower and student training:**

  An appropriate scientific manpower level is obviously needed to do the science effectively. Beyond this, the training of young scientists is one of the major returns on the basic research investment. The scientists and technologists trained in the nuclear physics program serve the nation in many ways (science, health, security, environment, economy) and sustain DOE core competencies.

- **Contribution to DOE Mission:**

  The elements listed above indicate that the nuclear physics program is well aligned with and strongly contributes to the five goals expressed by DOE for its Science and Technology vision.

- **Long-Range Planning:**

  The value of the Long Range Plan process to nuclear physics, to the agencies, and to the nation has been demonstrated repeatedly over the last fifteen years. It provides the framework for consensus on new initiatives and difficult priority choices and for the commitment of financial resources and of scientific careers. The framework for NSAC priority discussion is absent when the boundary conditions implicit in Long Range Plan recommendations are drastically altered. The long range planning partnership needs renewal.

APPENDIX

Department of Energy
Washington, DC 20585
February 24, 1994

Professor Ernest Moniz, Chairman
DOE/NSF Nuclear Science Advisory Committee
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Professor Moniz:

The DOE/NSF Nuclear Science Advisory Committee (NSAC) has not updated its planning advice for the Department of Energy Nuclear Physics program since 1992. NSAC is requested to prepare a report providing scientific guidance to help plan future Nuclear Physics programs. The present program status should be assessed against the scientific priorities contained within existing recommendations. Needs and priorities should be discussed within the framework of the Long Range Plan and subsequent NSAC reports. To be most useful to the Department, the report should be completed by the end of April 1994.

In addition, NSAC will undertake a broader study of the value and contributions of nuclear physics in the context of emerging national scientific priorities, and to recommend strategies for managing the program within that context.

Sincerely,

William C. Harris
Assistant Director
Directorate for Mathematical and Physical Sciences
National Science Foundation

Martha A. Krebs
Director
Office of Energy Research
U.S. Department of Energy