Nuclear Science: A Long Range Plan

The DOE/NSF Nuclear Science Advisory Committee

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OVERVIEW

Introduction

Nuclear science has as its objective the understanding of nuclei, which are the hearts of atoms and the place where almost all of the mass of ordinary matter resides. Despite the ubiquity of nuclear matter in the universe, understanding its behavior is a major challenge. Nuclei are assembled in stars from individual protons and neutrons, and nuclear properties are governed by their motions and interactions within the nucleus. But, at a deeper level, protons and neutrons themselves are found to have a complex structure, being composed of quarks and gluons that seem forever trapped inside. And yet, we believe quarks and gluons roamed independently during the first microsecond of the universe's existence, when the temperature was greater than 10^{12} degrees Kelvin. Quantum Chromodynamics (QCD) is considered to be an exact description of the interaction of the quarks, but the complexities of the theory make the way in which nuclear matter is constructed from quarks still mysterious.

Solving this problem is essential to understanding matter under both normal conditions and conditions very far from normal. Extreme conditions existed in the early universe, exist in the cores of stars, and can be created in the laboratory during collisions between nuclei.

While many important issues remain to be resolved, the progress already made in nuclear science is remarkable. There is now a clear understanding of the role of the various forces of nature that shape nuclei (only gravitation plays no role in ordinary nuclei), of how the elements were produced in the cosmos, and of the importance and surprising intricacy of symmetry in nature's blueprint for matter. With that understanding has come clarity and consensus as to basic questions that must now be answered, and delineation of the facilities and capabilities needed to answer them. Even though one cannot anticipate the answers in basic research, the return on the public's investment can be maximized through long-range planning of the most promising avenues to explore and the resources needed to explore them.

The following chapters contain an extensive discussion of major scientific accomplishments since the field was reviewed for the 1989 Long Range Plan, the opportunities for the future, our recommendations, and the resources needed to achieve success.

Some readers may prefer to obtain a more general flavor of the activities rather than details about the science, the applications, and the education associated with nuclear physics. We have therefore included a set of "sidebar pages" (the pages with blue backgrounds distributed throughout the relevant chapters). We urge the general reader to browse through the sidebars to identify those of interest. While far from inclusive, the examples shown in the sidebar pages together with this overview should give readers a picture of some of the accomplishments, opportunities and goals of nuclear science. (Note: nuclear science includes both nuclear physics and nuclear chemistry, but this document often uses "nuclear science" and "nuclear physics" interchangeably.) For those who use the Internet we have included an Appendix listing a number of World-Wide-Web addresses that contain information about nuclear physics activities and facilities.

The Scientific Questions

Modern nuclear science research can, broadly speaking, be subdivided into four scientific thrust areas, which are described in Chapters I to IV.

I. Nuclear Structure and Dynamics: Exploring the Limits

Nuclear science is pushing at new frontiers of spin, of temperature, and of nuclear stability by building upon the foundation of greatly increased understanding of nuclear structure and reactions earned over the last decades. For example, the study of highly deformed shapes and the discovery of new nuclei provide stringent tests to advance our understanding of nuclear structure. The unexpected discovery that many nuclei generate identical "fingerprints" (rotation spectra), to a precision better than a part per thousand, demands understanding. New experiments with beams of short-lived radioactive nuclei will push this frontier and address many important astrophysical issues, such as creation of the elements.

II. To the Quark Structure of Matter

Quantum chromodynamics (QCD) is the basic theory describing the interactions of quarks and gluons, the underlying constituents of strongly interacting matter. However, the way in which quarks and gluons are confined within the nucleons (the protons and neutrons that make up all nuclei), and within the mesons, whose fleeting existence generates nuclear forces, is poorly understood in QCD. New capabilities with electron, photon, and proton beams will permit comprehensive studies of this fundamental issue over the next decade and ultimately provide a bridge between QCD and the current description of atomic nuclei and nuclear forces in terms of hadrons (nucleons and mesons).

III. The Phases of Nuclear Matter

Most studies of nuclear matter to date have explored and clarified its properties at or near normal temperatures and densities. As with ordinary materials, phase changes occur with a change of conditions (such as water to steam). Two kinds of nuclear phase change are regarded as likely to occur, and tantalizing glimpses of the first may have been seen in recent experiments. Heavy-ion collisions at intermediate energy will explore what appears to be the analog for quantum systems of a liquid-gas phase transition. At still higher energy densities, the transition from hot dense nuclear matter to a quark-gluon plasma is anticipated. This latter phase of matter, in which quarks and gluons are deconfined, existed for only several millionths of a second after the Big Bang and may exist today in the cores of neutron stars. Ultrarelativistic heavy ions are the best way to create and study the quark-gluon plasma in the laboratory.

IV. Fundamental Symmetries and Nuclear Astrophysics

Precision experiments at low and intermediate energy using nuclei and the techniques of nuclear physics continue to play an essential role, complementary to high energy experiments, in probing the limits of the Standard Model. This theory, which includes QCD together with the electromagnetic and weak interactions, successfully incorporates the known elementary particles and forces but is clearly incomplete. For example, the masses of most of the elementary particles are not predictions, but empirical constants, of the theory. Observation of tiny violations of fundamental symmetries can provide crucial guidance towards new theories. A fundamental issue for physics, astrophysics, and cosmology, and a major research area in nuclear physics is the question of whether neutrinos (particles like electrons, but with no charge) have mass. The Standard Model says they do not, but evidence from nuclear physics hints that they may. Nuclear physics is also increasingly central to the resolution of a host of astrophysical issues, from cosmology to stellar structure. New detectors now under construction are expected to yield results of fundamental importance in the coming decade.

Nuclear Science in the National Interest

The goal of nuclear physics research is the understanding of matter at a fundamental level. Nuclear physicists answer questions about how this matter has formed, how it is held together, how it is structured, how it interacts in collision, and how it is transformed in stellar interiors. Pursuit of this goal entails developing new technologies and advanced facilities, educating young scientists, training a technical workforce, and contributing to the broader science and technology enterprise through the many intersections of nuclear physics with other disciplines. The knowledge, technology and well-trained young scientists that result from nuclear physics research will continue to yield a rich harvest of future applications and benefits for both science and society.

Basic research has benefits that extend far beyond the original search, often in completely unexpected ways. Nuclear science, a research activity that is today funded at the several-hundred-million dollar level, has been the basis of business activity that now totals tens of billions of dollars per year. Nuclear medicine, nuclear power, the very security of the nation itself, are but a part of that activity. No less important are the individuals from whose creativity the nation has benefited; one-eighth of all Ph.D.'s awarded in physics in the U.S. are trained in nuclear physics. The reader is invited to look through Chapters VII and VIII to see the remarkable influence of nuclear science on the nation's well-being.

The Long Range Plan

This Long Range Plan (LRP) builds upon and extends those prepared by the Nuclear Science Advisory Committee (NSAC) in 1979, 1983 and 1989. The LRP process has been successful in establishing a dialogue of consequence among the nuclear science community, the Department of Energy, the National Science Foundation, Congress, and the Administration. The agencies jointly charged NSAC in September 1994 to provide a new study of scientific opportunities and priorities and to address the question of equipment and facilities needed in the future. The full charge is reproduced in the Appendix.

In preparing a response, NSAC sought and received extensive community input. We collaborated with the Division of Nuclear Physics of the American Physical Society in sponsoring six town meetings, held from coast to coast. Many hundreds of scientists participated, producing "white papers" summarizing progress and prospects in different parts of nuclear science. Additional reports were generated by community groups with more specific interests. Presentations were made to NSAC by management of each of the user facilities. Finally, a balanced group of sixty-four nuclear scientists, the Long Range Plan Working Group, met in Pasadena, California during March 16-21, 1995 to fold all of this input into this Long Range Plan for Nuclear Science. We benefited from the participation of representatives from nuclear science advisory committees in Europe and Japan. This document is the result of that effort.

The Long Range Plan puts forward the nuclear science community's goals and priorities for addressing fundamental questions in the four thrust areas of research. It recommends a program that will significantly advance those research directions while educating a new generation of scientists. The program outlined is one with extraordinary discovery potential, but it can only be achieved within the budgetary guidance contained in the agencies' charge to NSAC. This important topic is discussed at greater length at the end of this Overview and in Chapter IX.

The major scientific thrusts define a set of requirements for the science, and the last decade has seen substantial investments in people, ideas, instrumentation, and facilities. Facilities in operation and under construction are described, and recommendations for upgrades and future facilities driven by scientific priorities are presented in Chapter V. The forefront facilities both in the United States and abroad attract significant international scientific collaboration, and opportunities for enhanced collaboration are discussed in Chapter VI.

This Plan presents progress and prospects in nuclear science activities beyond those associated with forefront research. Education of the next generation of scientists is an important corollary of fundamental research, and nuclear physics contributes substantially in this area. Another corollary is use of the unique assets of the nuclear physics research enterprise to improve public scientific and technical literacy in general. The commitment to such activities is steadily growing, as the reader will discover in Chapter VII.

The scientific and educational priorities and recommendations arrived at by the Long Range Plan Working Group are presented in Chapter IX, together with an analysis of the funding resources required to carry out the program. The proposed program builds upon and extends that framed by earlier Long Range Plans and thereby renews the process of responsibly shaping the nation's investment in a continuing world-class nuclear science program at the dawn of the twenty-first century.

The Recommendations are summarized below in boldface type with explanatory information in the accompanying paragraphs. The full text is given in Chapter IX.

Recommendations

1. The highest priority for U.S. nuclear science is vigorous pursuit of the scientific opportunities provided by the nation's recent investments in forefront instrumentation and facilities. Scientific, technological and educational returns commensu-

rate with these investments will require resources consistent with those in the charge requesting this Long Range Plan.

The assignment of highest priority to utilization of the array of new tools and facilities is consistent with maximizing the return on investments already made and is clearly important in this time of great pressure on federal resources. If fully utilized, these investments will greatly advance our understanding of strongly interacting matter, which is the goal of the field. The Scientific Facilities Utilization Initiative of the DOE precisely addresses this need, the highest priority for nuclear science, and its continuation and reinforcement are most important. The recommendation applies *equally* to the very large facilities CEBAF and RHIC (once it begins operation) and to the lower-energy facilities at universities and national laboratories, and to detectors that provide essential complements at the nuclear-physics frontiers. It entails support for the scientific personnel needed to carry out the experiments, provide the theoretical framework, and educate the next generation through strong university programs. It requires an ongoing level of investment in new instrumentation to meet evolving scientific needs. The funding guidance supplied to NSAC for this Long Range Plan, although substantially more constrained than earlier projections, will permit a productive program. This forward-looking and balanced program has been achieved at the cost of significant and difficult program reductions, which have been effected since the 1989 Long Range Plan.

Clearly, very large facilities require especially careful planning and sustained commitments. In this regard, completion of CEBAF and the start of RHIC construction represent significant milestones in the NSAC long range planning process. Timely completion and operation of CEBAF was the highest priority in the 1989 Long Range Plan, reflecting the nuclear science community's commitment to a multi-GeV, high intensity, continuous electron beam facility recommended in the 1979 Long Range Plan. CEBAF has started its important science program this year. As the world's most powerful "microscope" for probing the electromagnetic structure of nuclei, CEBAF will provide essential data for bridging the hadronic and quark descriptions of nuclear matter . A large user community invested an enormous effort in the design and construction of experimental apparatus and is now beginning to explore the physics. The laboratory should now be operated at a level commensurate with the investment and the science opportunity. With the superconducting accelerator technology at CEBAF performing so well, the community looks forward to future increases in CEBAF's energy, and to the scientific opportunities that would bring.

2. RHIC remains our highest construction priority. Its timely completion and operation are of utmost importance for discovery of the quark-gluon plasma and for study of this new form of matter.

The highest priority for new construction in the 1989 Plan was the Relativistic Heavy Ion Collider (RHIC). Its principal goal is to study, in the laboratory, matter at the highest achievable energy densities, as it existed in the early universe. The transition to deconfined matter, that is, matter in which the quark and gluon constituents of protons, neutrons, and other hadrons are able to propagate over significant distances, is a fundamental prediction of QCD. Establishing this transition will represent a major step in scientific exploration of the world about us. RHIC construction is now well advanced and is on schedule for a 1999 completion date. The unique opportunities to discover and study new phenomena at RHIC have led to the formation of vigorous international collaborations whose members are investing major efforts in advanced detectors suited to RHIC's unexplored regime of ultrarelativistic heavy-ion collisions.

Initiatives

A number of facility initiatives and upgrades that would greatly enhance U. S. capabilities in nuclear science have been proposed. Within the financial boundaries of our charge (discussed below), we recommend selected initiatives in the areas of radioactive beams and hadron beams.

The ability to create nuclei at the limits of stability has generated world-wide scientific interest. Near those limits, new regularities are anticipated, the presence or absence of which would profoundly influence our understanding of nuclear structure and the symmetries governing nuclear behavior. Results from first-generation programs of limited scope being pursued in the U.S. have heightened the interest. New capabilities would allow a robust program of nuclear structure studies in a new domain that is also central to understanding the stellar processes through which the elements are synthesized.

3. The scientific opportunities made available by world-class radioactive beams are extremely compelling and merit very high priority. The U.S. is well-positioned for a leadership role in this important area; accordingly

• We strongly recommend the immediate upgrade of the MSU facility to provide intense beams of radioactive nuclei via fragmentation.

• We strongly recommend development of a cost-effective plan for a next generation ISOL-type facility and its construction when RHIC construction is substantially complete.

The fragmentation and Isotope Separator On-Line (ISOL) techniques are complementary in the species and energies of the beams produced. Thus, they drive different aspects of the science. The MSU (Michigan State University) upgrade can be accomplished on a relatively short time scale. Within the budgetary constraints of our charge, construction of a major ISOL-type facility must wait several years, until RHIC construction is substantially completed, for the bulk of its funding.

Proton beams, and the secondary beams of neutrons, mesons and leptons derived from intense primary proton beams, are a major part of the arsenal for research in nuclear science. The community has experienced significant loss of opportunity in this regard with the closure of LAMPF as a nuclear physics user facility. On the positive side, significant new capabilities with electromagnetic probes will address related physics, selected experiments with intermediate energy pion and lepton beams will still be possible at LANSCE (the Los Alamos Neutron Science Center), the technology for polarizing protons in storage rings has been developed and utilized effectively, and the intensity of kaon beams at the Brookhaven AGS has been increased significantly. These developments lead to important scientific opportunities with hadronic beams at existing facilities, and point to new directions.

4. Multi-GeV proton beams are an essential tool for forefront studies aimed at elucidating the quark structure of nucleons and nuclei.

• We strongly recommend funding for the Light-Ion Spin Synchrotron (LISS) as a major NSF research equipment initiative. This facility will build on Indiana University's leadership in stored, cooled, polarized proton beam technology to enable innovative experiments addressing the short-range behavior of nuclear forces.

• The RHIC/AGS complex, in addition to its core heavy-ion program, will offer significant capabilities with hadron beams. In particular, the collisions of polarized proton beams in RHIC will enable unique studies of quark and gluon distributions inside the nucleon. These studies are important for understanding hadron structure and should be pursued.

The experimental programs at these two facilities would be especially important in unraveling the quark basis of short-range nuclear interactions and in providing new insights into quark and gluon distributions.

Recent advances in storage-ring accelerator technology, principally at Indiana, provide the basis for LISS, a cooler ring that would provide 15-GeV polarized proton beams of exceptional quality. Construction would require approval as an NSF major research equipment initiative, helped by substantial local matching funds.

Polarized protons in RHIC could be collided at total energies as high as 500 GeV. Studies using these beams would be of interest to both nuclear and high-energy physicists and would require modest incremental operating costs. The RHIC spin program has elicited significant international contribution and would be scheduled as the RHIC heavy-ion program permits. In addition, when the AGS is not being used as an injector for RHIC, extracted beams could be made available for specific experiments on the basis of scientific merit.

Instrumentation

While Recommendations 2, 3, and 4 focus on facilities, there are substantial infrastructure issues that must be addressed in order to pursue our first priority, that of capitalizing scientifically on the investment in frontier opportunities. Instrumentation initiatives of modest scale are at the core of forefront scientific investigation and often contribute significantly to student education and to university technical infrastructure. While instrumentation tends to be regarded as the province of the experimentalist, the theoretical community sees a need for substantially increased computing power to address problems ranging from nuclear structure to first-principles calculations in QCD. Innovative proposals in both experiment and theory are coming forward regularly in step with scientific, technical, and facility progress. It is essential to allow flexibility to respond through peer review to the most promising proposals.

5. We recommend an increase in equipment funding.

Many innovative projects addressing key issues in all of the major scientific thrust areas, and of moderate cost, could be pursued if equipment funds were available for them.

Theory

Our science is based on observation and measurement, and the recommendations above largely focus on provision of the necessary experimental tools. However, significant progress depends crucially on the partnership and synergy between experiment and theory. The wealth of scientific challenges, including the significant intersections with astrophysics and particle physics, places continuous demands on the creativity of the theoretical community. A particularly good example of a successful initiative in theory is the Institute for Nuclear Theory at Seattle, established in 1990, which has had a very stimulating effect in establishing new directions, forging new collaborations, and fostering theoretical progress in support of major experimental programs.

6. A strong nuclear theory effort is essential for continued progress at the emerging frontiers of nuclear science. We recommend continued strengthening of the theory program.

International Collaboration

International cooperation in nuclear physics has been and will continue to be extremely lively and productive at the scientist-to-scientist level. With the increased scale of major facilities, a number of more formal cooperative agreements have been pursued to open up scientific opportunities for the international community at unique facilities. In turn, these facilities have been able to extend their scientific reach through instrumentation development by the international partners.

7. We recommend that dialogue and collaboration among the major international nuclear science communities, and most specifically discussion among their representative advisory committees, be continued and extended. These discussions should provide input to the nuclear science planning activities of the governments supporting these research communities.

Education and Outreach

Education of the next generation of scientists is a very important corollary of fundamental research, and the nuclear science community contributes substantially in this area. As we have mentioned, nuclear physics research annually yields more than one-eighth of the nation's Ph.D.'s awarded in physics. Regardless of the exact career paths followed by these individuals, they collectively possess nuclear science and technology competencies which are a critical element in our national workforce. Predictability of funding over a time period of several years is essential for sustaining an appropriate level of graduate training.

In addition, nuclear physicists contribute to broadening the overall education of undergraduates by offering them opportunities to participate in challenging research projects. Nuclear physics offers some special opportunities for undergraduates, such as on-campus accelerator environments and collaboration in research teams. The NSF "Research Experience for Undergraduates" program has been a notable success. A second important effect of fundamental research stems from the use of the unique assets of the research enterprise to improve the public's scientific and technical literacy. Nuclear physicists are very active in programs that strengthen pre-college science and mathematics education, and we believe these activities to be part of the responsibility of our research community.

8. We urge that the funding agencies sustain and indeed strengthen their support for the efforts of the nuclear science research community to make effective use of its unique facilities and experience to enhance science education, improve public scientific literacy, and expand further its outreach activities from grade school to graduate school.

Applications

Nuclear-physics techniques have provided important tools for many disciplines in science and technology, and nuclear scientists continue to find new and original ways to meet societal needs, contributing substantially to the national interest. In addition to the direct benefits, these aspects significantly enrich the environment for graduate education and undergraduate research.

9. We support increased opportunity for interdisciplinary research and for initiating promising applications of nuclear science and technology towards societal goals.

Resources

NSAC received explicit budgetary guidance from the agencies for developing this Long Range Plan. For the Department of Energy, our Plan addresses FY 1997 budgets between $325M and $350M and then goes forward at a constant level of effort (interpreted as constant spending power). The high end of the charge corresponds to the FY 1995 budget adjusted for inflation; the low end corresponds to a 7% reduction from FY95, adjusted for inflation. For the National Science Foundation, the charge specifies a constant level of effort starting from the FY 1994 budget of $42.2M. In our charge, the FY 1996 DOE and NSF budgets for nuclear physics were anticipated to provide a "reasonable transition" to the specified FY97 levels.

The budgetary recommendations, driven by the priorities summarized above, are elaborated in the body of this Plan (Chapter IX). While the principal focus of the resource needs is effective utilization of the instruments and facilities completed or well underway, we provide for high priority initiatives of modest cost within the budgetary framework. Such initiatives are integral to forefront and to the training of creative young scientists. The opportunities and impact of both the upper and lower ranges of the budgets are discussed in some detail in Chapter IX. Funding levels in the range of the guidance provided to NSAC would provide for a research program with outstanding discovery potential and with important benefits to the nation in education and technology development.

As requested by the agencies, our principal recommendations and discussion of resource needs were issued in an interim report in April 1995. Budget concerns have become acute since that report was issued. The DOE budget and, very likely, the NSF budget for nuclear physics in FY96, will be below the Long Range Plan guidance. Specifically, the FY96 total DOE + NSF nuclear physics budget appears to be about $340M, well below both the FY95 allocation of $375M and the FY97 allocation specified in the charge, namely, $375M to $400M. The FY96 shortfall exacerbates the situation caused by an approximately 20% decline in spending power over the last several years (the FY94 combined allocation of the two agencies was $391M), which has forced termination of scientifically productive programs.

Since the 1989 Long Range Plan, the large funding reduction, coupled with the ongoing desire to address forefront scientific issues with new capabilities, has resulted in the closure of several major facilities. The NSF ended operations at two university-based accelerator facilities and reduced support at others. The Bevalac and LAMPF were closed as DOE-supported user facilities. These latter two were the largest nuclear-physics facilities in 1989, had strong records of achievement, and were continuing to do important research with large user communities. Nevertheless, they could not be accommodated within the decreased budget while CEBAF and RHIC were being developed. These two major new facilities, which have been carefully woven into the nuclear physics program over the past fifteen years in consultation with the funding agencies and Congress, are projected to have a combined operating cost of nearly one half the DOE budget provided in the charge. In addition, their university and national laboratory users and major new experimental equipment needed in the future for the evolving science programs must be provided for.

This recent history is important insofar as it affects the future. The major scientific objectives of this Long Range Plan can be met within the stringent fiscal boundaries defined in the charge to NSAC, and the nuclear science community will continue to shape the public's investment judiciously. The research and educational program will be important for science and for the nation. The recommendations and priorities offered in the April, 1995 interim report remain those that have the community's support.

However, as is evident from the hard choices already made since the last Long Range Plan, core research and educational activities have already been seriously impacted. Further retrenchment in the overall support levels (below those specified in the charge to NSAC), particularly in light of the long understood funding requirements for CEBAF and RHIC, would necessarily cut more deeply into exciting and productive research, impact university programs and compromise the balanced investigation of the nuclear science frontiers. That would be wasteful not only of the nation's investment in nuclear physics research and in its scientists, but also of the opportunities for scientific progress on several fronts. We thus stress the importance of funding levels consistent with the Long Range Plan guidance.

The value of the NSAC Long Range Plan process both to the nuclear science community and to the supporting agencies and Congress has been demonstrated repeatedly over many years. It has provided the framework for consensus on major initiatives and difficult priority choices and for the commitment of financial resources and scientific careers. This Long Range Plan builds upon and extends the earlier Long Range Plans, renewing the process of responsibly shaping the nation's investment in nuclear science through a partnership between the research community and the public. The return on that investment is world leadership in nuclear science.

I. NUCLEAR STRUCTURE AND DYNAMICS: EXPLORING THE LIMITS

Scientific Motivation

The nucleus is a quantal many-body system governed by the strong interaction. The study of its properties is an exploration of the symmetries and degrees of freedom that define such a system. The ideas and methods employed have a large overlap with other areas of many-body physics both fundamental and applied. Results from nuclear structure research are important for our understanding of astrophysical processes and the nucleosynthesis that produced the chemical elements of the world in which we live.

Nuclei display a remarkable range of phenomena. The symmetries and degrees of freedom that govern the nucleus are intimately connected to the length and energy scales at which we observe them. The nucleus as a whole exhibits collective behavior, reminiscent of liquid drops but with distinct quantum features such as superfluidity. On this scale motions of individual nucleons, protons and neutrons, are seen as motions in an average potential created by the interactions between all nucleons. Collective and single-particle modes can couple to each other leading to new phenomena and symmetries.

This picture of nuclei and the strong interaction is based on nucleons and the exchange of mesons. The resulting phenomenological model of the nuclear force, with nucleons exchanging pions and heavier mesons, has provided a rather successful basis for describing many nuclear observables. Yet this picture is incomplete and valid only over a limited range of conditions.

At high energies and consequently small distance scales, nucleons and mesons are known to be composites of quark and gluon fields. The strong self-interaction between the latter appears to lead to the confinement of quarks. The interaction between nucleons is the residue of the quark and gluon confining interactions inside the nucleon: the internal structure of nucleons and mesons and the strong interaction between them are intertwined. When nucleons are far enough apart, as generally is the case in nuclei, this residual interaction is approximated by representing it as an exchange of pions.

The range of phenomena observed in nuclei, going from subnucleon structure on the one end to the mean-field behavior of the nuclear medium on the other, spans the range of questions addressed by nuclear structure studies. The dialectic and the commonality in these studies is illustrated with the example in Figure I.1. It shows contour lines of constant density for the smallest nucleus, the deuteron, which consists of a single proton and neutron, and for a heavy nucleus with more than 150 nucleons. Both deviate from spherical symmetry. In the former case, the deformation arises as a direct consequence of a component of the nucleon-nucleon interaction, the tensor force, which is a characteristic feature of pion exchange. In the latter case, the mean field of the many-body system generated by the nuclear forces is responsible for the strong deformation.

As in any other physical system, measurements at the limits can provide important simplifications that shed light on the underlying symmetries and lead to new insights and understanding. New instrumentation is enabling the creation and study in the laboratory of nuclei at the very limits of their existence: the heaviest nuclei, barely holding together against the repulsion of their electric charge; nuclei under stress from rapid rotation; nuclei at high temperatures and close to evaporation; nuclei far from the valley of stability with extremes in proton-to-neutron ratios; and nuclei with strangeness. New opportunities for microscopic explorations have been opened by precision studies of few-nucleon systems and of nucleon orbitals deep inside heavier nuclei.

The experimental program in nuclear structure advances in concert with important developments in nuclear theory. New ideas, increased computer power and progress in computational techniques have greatly enhanced our ability to address the nuclear many-body problem at a microscopic level. For light nuclei, Monte Carlo variational calculations based on realistic interactions predict binding energies and wave functions. Calculations of nuclear structure based on the shell-model can now be made more realistic. A new method to solve the shell model by functional-integral methods offers a microscopic description of thermal properties and average

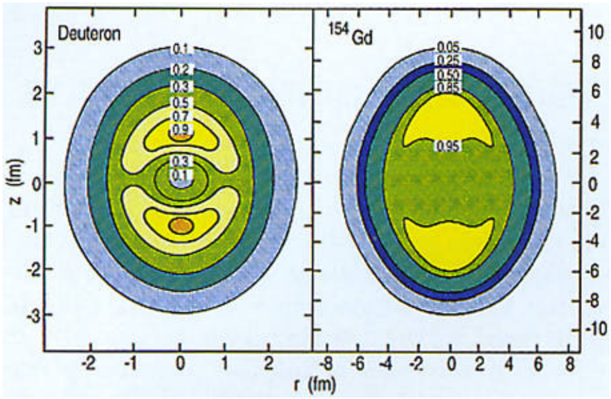

Figure I.1: Matter density contours for the deuteron (left) and the ^{154}Gd nucleus (right) deduced from experiment.

strength functions for medium-mass and heavy nuclei. The mean-field theory has been successful in describing nuclei at low and high angular momenta; predictions have been made for new elements and for exotic nuclei far from the stability line.

New sensitivities to important aspects of nuclear structure research have been realized through the unique accelerators and detectors located in university laboratories and small national facilities. Many advances in nuclear structure research and in nuclear astrophysics have followed the development of novel instrumentation, including that required to produce polarized nuclei as beams or targets and the new gamma-ray detector arrays such as Gammasphere (see Figure I.C). Still more powerful arrays are on the horizon. The radioactive ion beams now available have opened new dimensions in research on nuclei at their limits of stability. Such beams also provide key information on reactions that take place in our Sun and other stars. However, such beams are presently limited in intensity, species and quality. Exploiting the scientific opportunities offered by this technique for a better understanding of nuclear properties and for clarifying the basic energy conversion processes that result in the creation of elements in stars, requires a major future facility.

Nuclei far from the Valley of Stability

Until recently, the study of the behavior of nucleons in the quantal nuclear many-body environment has been mostly confined to nuclei near

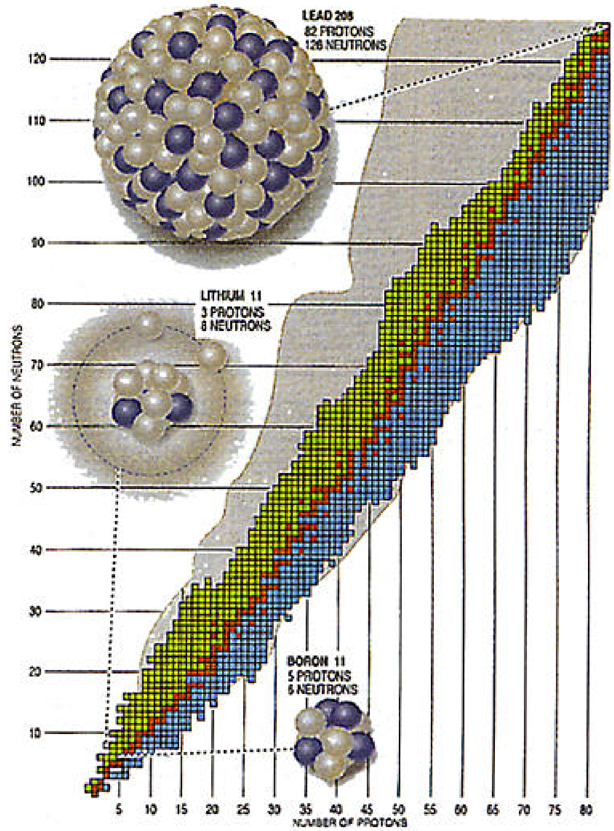

Figure I.2: Representation of the chart of nuclides: nuclei are given by squares, positioned horizontally according to the number of protons and vertically according to the number of neutrons. Stable nuclei are shown as red squares. Green squares indicate bound but unstable nuclei that have excess neutrons, blue squares mark bound, proton-rich nuclei.The outer borders of these regions are the 'drip lines' along which large halo nuclei, such as lithium-11, were recently found.

stability and to some proton rich nuclei. The stable nuclei that surround us constitute less than 10% of all the nuclear systems that should exist. They are represented by the red squares in Figure I.2. They are the energetically most favored and tightly bound nuclei, and are located at the bottom of the valley of stability. By adding either protons or neutrons one moves outward towards the ridges of the valley of stability, finally reaching the drip lines where the binding of nucleons ends.

The decay characteristics of most unstable nuclei are actually determined by the weak force which allows protons to convert to neutrons and vice versa by the emission of two leptons in each case ('beta decay'). Here the weak force plays a

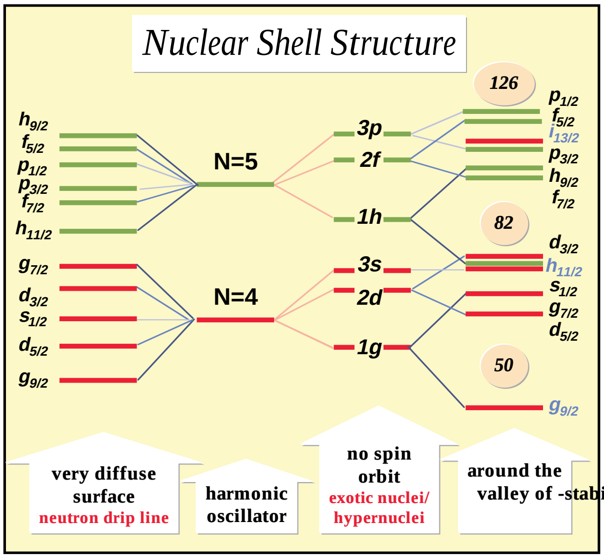

Figure I.3: Sequences of nuclear single-particle levels for various potentials. Levels are labeled by orbital (letters) and total angular momentum (half integers). Far right: Shell structure near stability (Nilsson potential) that best represents the mean field in normal nuclei. Right from center: No spin-orbit term, leading to a degenerate spin-orbit pattern as observed in hypernuclei. Left from center: The fully degenerate sequence of only two levels ($N = 4, 5$) for the harmonic oscillator potential. Left: shell structure for a potential with spin-orbit term but with a very diffuse surface; the total angular momentum values show a nested pattern, with successive orbits in most cases differing by two units.

fundamental role in shaping the features of the landscape of nuclei.

The advent of beams of short-lived, radioactive nuclei is providing new opportunities to create and study unstable nuclei far from stability. This opens an unexplored region of nuclei with the promise of new phenomena and new symmetries, possibly quite different from those in the stable regime. The effects on nuclear properties are expected to be largest near the drip lines, where the binding of nucleons (protons and neutrons) ends. If such modifications are confirmed, we will need to revisit our understanding of the atomic nucleus and of the diversity of quantal phenomena that it exhibits.

Since neutrons, unlike the positively charged protons, do not carry an electric charge and consequently do not repel each other, many neutrons can be added to nuclei starting from the valley of stability. The possibilities for new discoveries are especially intriguing near the neutron-drip line. The outer regions of such nuclei become nearly pure low-density neutron matter. Recent mean-field calculations suggest that such a matter distribution would give rise to a shell-model potential different from the usual one, and the pattern of single-particle orbits may change, causing shell structure to alter. A predicted weakening of the spin-orbit potential could cause further alterations in these orbits. Several such effects are illustrated in Figure I.3.

In concert with these changes in the potential, residual interactions will be dramatically altered. Protons and neutrons will occupy very different orbitals. Strong pairing fields are expected due to coupling with the particle continuum, and the valence proton-neutron interaction may change as well. Collective phenomena, and their evolution with neutron number N and proton number Z, will be different and the basic theoretical approach to near-drip line nuclei may well have to be reformulated. Indeed, near the neutron-drip line shell structure may be washed out and magic numbers may essentially disappear. Consequently, the many-body symmetries associated with shell structure near the valley of stability may become qualitatively different. Of course, if shell structure and residual interactions change, nuclear binding and the limits of nuclear existence will also be altered. Model estimates of the limits of stability, i.e., of the neutron-drip line, differ by up to 20-25 neutrons as illustrated in Figure I.4. The uncertainty for some elements is as broad as the span of known nuclei.

Recent experiments on light neutron-rich nuclei have already provided a first glimpse of some unexpected behavior. As shown in Figure I.2, nuclei, such as ^{11}Li, have revealed a neutron halo, i.e., a core surrounded by one or two weakly bound neutrons in spatially extended, diffuse orbitals. According to the Heisenberg uncertainty principle, this corresponds to narrow momentum distributions for such nucleons relative to the residual nucleus. This is illustrated in Figure I.5 with data for the ^{11}Be nucleus. Indeed such momentum distributions represent direct experimental evidence for the halos.

Related to halos are neutron skins, a more dramatic excess of neutrons on the nuclear surface, predicted to occur in heavier nuclei but with indications already seen in helium isotopes. In addition 5 to the new structures that such spatially extended systems manifest, they are also expected to exhibit unusual modes of collective excitations, such as dipole oscillations of outer

Matter That Lives But Milliseconds

The nucleus of an atom — a bundle of protons and neutrons held together by the strong nuclear force — is still a remarkably enigmatic object. Although nuclei account for 99 percent of all the matter around us, physicists still do not fully understand why some groupings of protons and neutrons are stable, and others are not. To add to the intrigue, it now seems clear that most nuclei are formed within stars by processes that depend on unstable nuclei — nuclei that mostly exist for a fraction of a second before they decay. Exploring the properties of such temporary matter is the key not only to a deeper knowledge of the structure of all matter but also to the astrophysical processes that have shaped our universe and have produced the stable elements that we ourselves are made of.

In a clever twist on the old admonition about “setting a thief to catch a thief”, physicists are now employing beams of unstable (radioactive) nuclei as a major new research tool to study the properties of unstable matter. They catch the radioactive nuclei to watch them decay, they react them with each other, and they use beams of them to make even more exotic (and unstable) nuclei. From such experiments, physicists can deduce the lifetimes, the energy releases, and the internal structures of these exotic nuclei.

To see what such studies can reveal, consider what happens as new nuclei are “cooked” inside a star. The star’s fierce energy comes from nuclear reactions that release both heat and large numbers of neutrons. One way nuclei inside the star can change and grow is by absorbing one neutron, then another, then another —forming heavier versions of a given element. Eventually, however, the nucleus would get so neutron- rich that it would literally fall apart. Before that happens, however, the nucleus often reaches a critical, if unstable, state in which a neutron inside the nucleus will decay into a proton, creating a new element. (The number of protons in the nucleus determines the element; for example, a carbon atom with 6 protons and

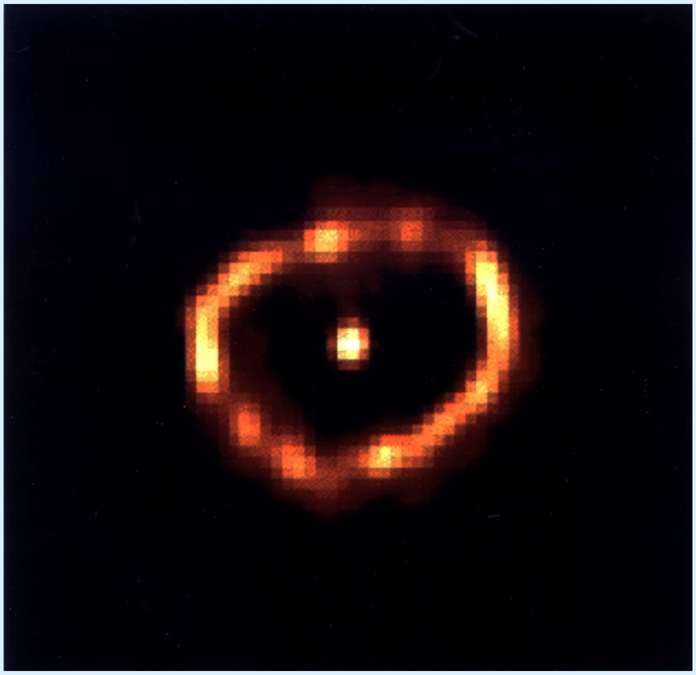

Figure I.A Nova Cygni 1992 as seen from the Hubble Space Telescope about six months after the explosion. The ejecta have spectra strongly indicative of an rp-process.

8 neutrons would become a nitrogen atom with 7 protons and 7 neutrons.) Then the neutron capture process can happen all over again for the new element, eventually creating yet another element. The point is that the critical steps in this nucleosynthesis process — those that limit the number of neutrons added and those in which neutrons become protons — all occur in unstable nuclei. Understanding the properties of such nuclei is thus basic to understanding the origins of matter.

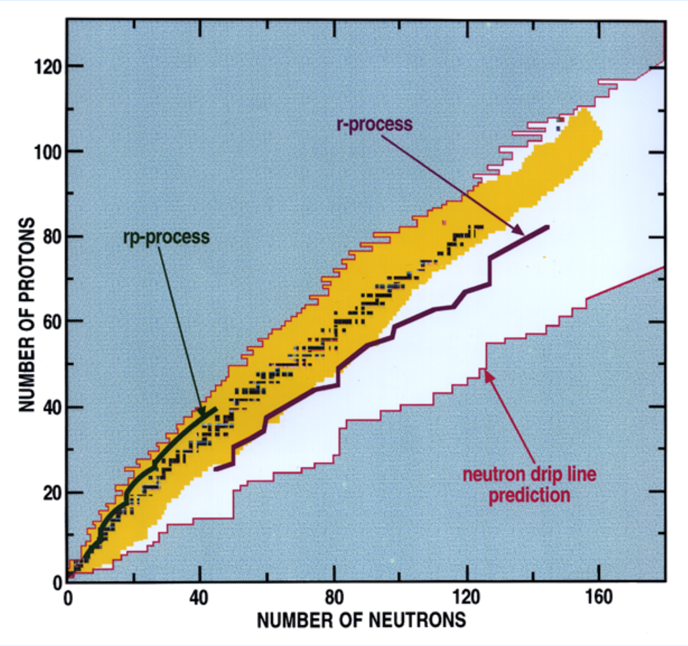

Figure I.B Chart of the nuclides, with the regime of known (yellow) and predicted (white) nuclei. The lower border of the white region is the "neutron drip-line", where addition of neutrons does not permit nuclear binding. The location of this drip-line is rather uncertain. Also shown are predicted paths of rapid, explosive nucleosynthesis occurring in nova explosions (via the rapid-proton process or "rp-process") and in supernova explosions (rapid neutron capture or "r-process").

Making heavy nuclei — roughly those heavier than iron, a group that includes copper, silver, gold, and uranium — requires so many neutrons and such high temperatures that cooking, even in a stellar furnace, won't do; an explosion is required. Thus all living things on Earth carry around in them nuclei that were first forged in the supernova explosion of a dying star — a still poorly understood astrophysical phenomenon. In such an explosion, the nucleosynthesis process proceeds, but at an accelerated rate and through nuclei that are even more unstable. Indeed, studies with radioactive beams are expected to determine the lifetimes of the critical nuclei in this process — and hence how long the supernova explosion must last if it is to grow nuclei all the way to uranium, for example. The new knowledge will thus help to explain these spectacular astronomical events.

In addition, physicists expect such experimental studies to shed light on the basic principles behind the structures of stable nuclei and to provide a glimpse of an entirely new area of nuclear physics. In this new frontier, there is every likelihood that the structure of nuclei may be quite different from anything physicists have yet observed. Indeed, some physicists have even speculated that very unstable nuclei may have exotic shapes or forms never before observed, but at present this is still unknown territory. Thus the allure of exploring the temporary forms of nuclear matter on which virtually all familiar forms of matter depend for their existence.

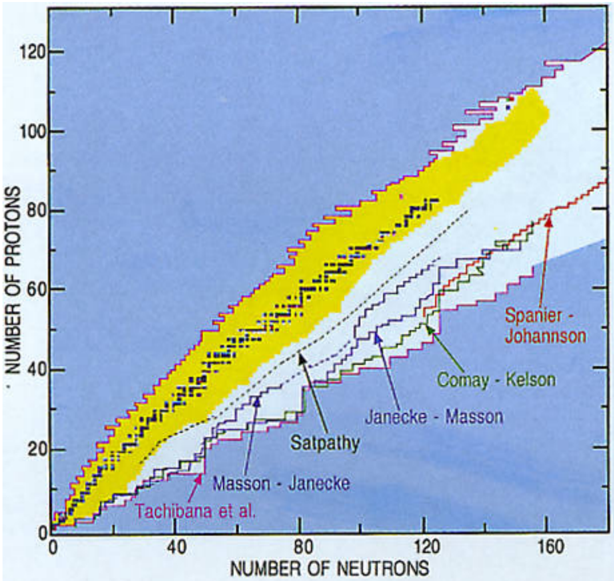

Figure I.4: Model estimates of the neutron-drip line illustrating the large uncertainties involved in precisely predicting where neutron binding in nuclei comes to an end.

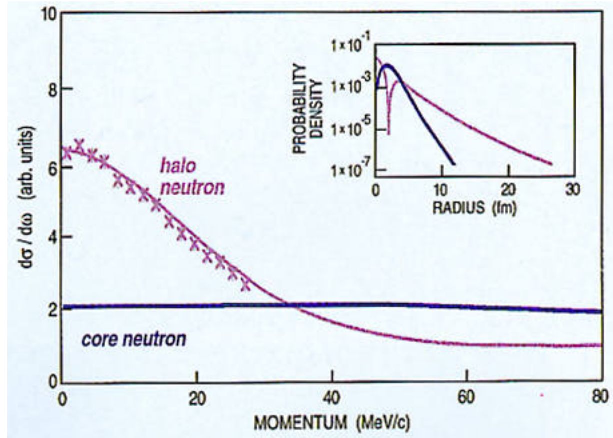

Figure I.5: Momentum distributions of a core neutron and of the loosely bound valence neutron in the nucleus ^{11}Be measured with respect to the residual nucleus by nuclear fragmentation at high energies. The data reveal the extended halo structure of the valence neutron's wave function relative to that of the core neutron, as illustrated in the insert.

neutrons against the core, or rotations of a deformed core inside a spherical neutron shell.

On the opposite side of the valley of stability, the proton-drip line lies relatively close to stability and can be studied all the way up to the lead nuclei with the use of short-lived, radioactive beams. Because of the Coulomb barrier, nuclei at and even beyond the proton-drip line are quasi-bound with respect to proton decay. The protons are literally dripping out of these systems and the associated lifetimes are generally short but may range up to seconds. The lifetimes for proton emission are sensitive to the quantum numbers of the parent and daughter states, and to the form and shape of the potential in the surface region, but do not have the uncertainties in interpreting them that are associated with cluster preformation that characterizes alpha decay. The study of deformed proton emitters will be particularly interesting as a tractable example of three-dimensional quantum tunneling. More exotic decay modes, such as correlated 2-proton emission, are also predicted.

Heavy self-conjugate nuclei, those with equal numbers of protons and neutrons, have special properties. In nuclei with unequal numbers of neutrons and protons ($N\neq Z$), superfluidity occurs for the neutrons or for the protons independently. Due to a high degree of spatial correlation between the protons and neutrons when $N=Z$, a new form of proton-neutron superfluidity (T=0 pairing) is predicted but has not yet been observed. If such p-n superfluidity is found, an important issue is how quickly it disappears when moving away from the $N=Z$ line and as Coulomb effects grow in importance. An additional important feature of these $N=Z$ nuclei is that the fastest and best understood beta decays occur in their immediate vicinity and provide important tests for the Standard Model.

Beams of short-lived, radioactive nuclei will allow access to all such bound systems up to, and possibly beyond, mass 100. The heaviest self-conjugate nucleus, ^{100}Sn, which was recently discovered, is expected to be doubly magic, i.e. to have closed proton and neutron shells. With proton-rich radioactive beams, the structure of ^{100}Sn and neighboring nuclei can be studied using inverse fusion reactions on light targets, combined with state of the art systems for gamma-ray detection and recoil identification. One-nucleon transfer reactions, particularly in the vicinity of closed-shell nuclei such as ^{100}Sn and ^{132}Sn, will disclose the single-particle structure of these systems, as will measurements of effective interactions extracted from particle-particle multiplets in their vicinities. Evidence for shell structure different from that observed near stability may already show up, for instance, in measurements of the lowest states of even-even nuclei whose simple recurring patterns are sensitive to the underlying single-particle structure.

Nearly all studies of high-spin states in nuclei to date have focused on proton rich nuclei. With neutron-rich radioactive beams, fusion evaporation reactions on neutron-rich (stable) targets allow the study of nuclei at high spin in the valley of stability, where such information can be combined with the wealth of existing knowledge on low-spin states. Hyperdeformation at high spin (the predicted extreme elongation of nuclei at high angular momentum) and new regions of reflection-asymmetric nuclei are predicted to occur on the neutron-rich side of the valley of stability. Finally, fission of neutron-rich nuclei at high spin would give access to lighter nuclei far more neutron rich than any produced to date.

As already mentioned, beams of short-lived nuclei far from stability allow laboratory studies of processes that are fundamental to the creation of the elements in explosive nucleosynthesis and in stars. This synergy between areas of nuclear and astrophysical research is discussed in detail in Chapter IV. Here we want to discuss one example that illustrates the use of radioactive beams for such studies. Short-lived, secondary beams have been produced recently through in-flight fragmentation of stable nuclei from existing high-energy heavy-ion accelerators. Often the mere existence or non-existence of nuclei near the limits of stability can provide important clues to astrophysical processes. This is illustrated with the example in Figure I.6 where the distribution of nuclei observed in fragmentation of a stable krypton beam is shown. The stability of the arsenic nucleus with mass number 65, and conversely the particle instability of the bromine nucleus with mass 69, both impact the time evolution of the rapid-proton capture process (rp-process) which propagates through this mass region, creating the proton-rich stable nuclei up to the elements around zirconium. The time scale of this process may influence the nature of the associated astrophysical scenario. Figure I.A shows a picture taken with the Hubble telescope from the outer ring of matter blasting into space from the 1992 nova in the Cygnus constellation. The prominence of emission lines from neon atoms in simultaneously recorded optical spectra, as well as those observed of heavier elements, are consistent with the explosive evolution of this stellar process being driven by the nuclear reactions of the rp-process.

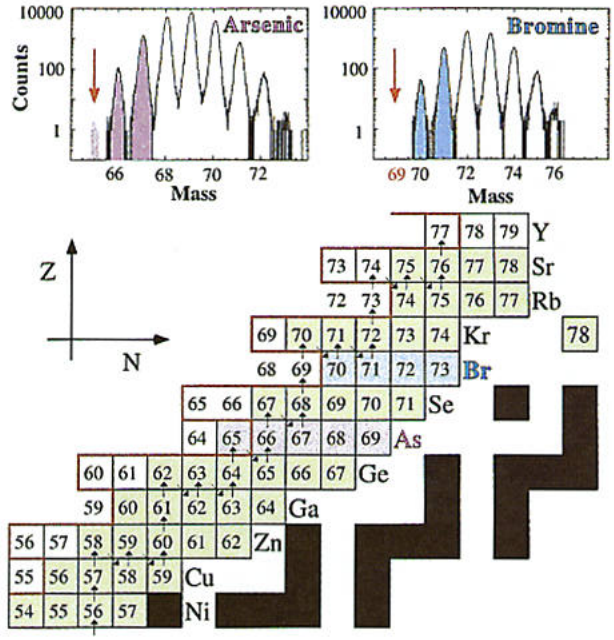

Figure I.6: Distribution of nuclei produced in the fragmentation of a stable krypton nucleus. The stability of the nucleus ^{65}As and the particle instability of the nucleus ^{69}Br are relevant for the path which the astrophysical rapid-proton capture process takes in this region of the nuclear chart (the small arrows represent a previous prediction), and for its evolution in time in the explosive burning at the surface of a star.

The Heaviest Elements

The existence, stability, and synthesis of the heaviest elements have been persistent themes in nuclear physics. The mere existence of these nuclei is a sensitive manifestation of nuclear shell effects: above element 104 (Rutherfordium) the estimated barrier against spontaneous fission based on the liquid-drop model essentially vanishes due to the very large Coulomb energy. No heavier elements would be stable were it not for the stability provided by shell structure.

The last year has witnessed great strides in the production and study of the heaviest nuclei. Isotopes of the new elements 110 and 111 were synthesized. The discovery of these new elements was the result of an improved understanding of the reaction mechanisms and of improved target and detection systems. The relatively long half-lives of these heaviest nuclei support model calculations of enhanced stability in this region and give added confidence to predictions of very long shell-stabilized lifetimes (from 100 seconds to days) near the expected doubly-magic nucleus with 114 protons and 184 neutrons. Moreover, they suggest that binding and stability should increase as one advances toward this goal, and that the island of superheavy nuclei may be approached incrementally.

Despite these recent advances, further progress will be difficult experimentally. The successful 'cold' reactions for compound nucleus formation, i.e., reactions involving medium-heavy beams of stable nuclei incident on heavy stable target nuclei (lead and bismuth) which produced compound nuclei with very low excitation energy, cannot reach Z=114, N=184. Fusion evaporation reactions with lighter projectiles on heavier exotic actinide targets are difficult because of the low cross sections and the difficulty in obtaining suitable targets. These problems might be overcome by using beams of neutron-rich medium-mass radioactive nuclei on Pb or Bi targets, or of neutron-rich lighter nuclei on suitable actinide targets. Development of sensitive new instrumentation will be important. The predicted long half-lives of the superheavy elements could open exciting possibilities for the chemical studies of such new elements characterized by extreme values of the nuclear charge Z.

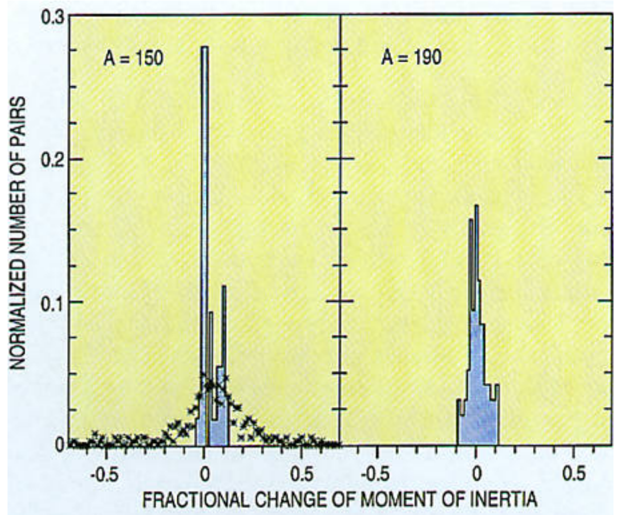

Figure I.7: Frequency distributions of pairs of observed rotational bands in neighboring nuclei as a function of the fractional change of the moment of inertia. The histograms represent data for superdeformed bands in two mass regions, for rare earth nuclei around mass A$\sim$150 (54 pairs) and for nuclei around A$\sim$190 (96 pairs). The stars are corresponding data points for nearly 400 normally deformed bands in the mass A$\sim$150 region. Both the superdeformed as well as the normally deformed bands shown in this comparison were selected under the condition that the relative angular momentum for a pair is linear in total spin I. All distributions are separately normalized to a total count of unity.

New Aspects of Nuclear Rotation and Vibration

A persistent theme in the history of the field of nuclear structure is one where the limits of what can be resolved are steadily expanding. These improvements have consistently led to new discoveries and insights into the nature of the nucleus. Recent advances in high-resolution gamma-ray detector systems, such as Gammasphere, are responsible for a revolution in our study of the properties and response of nuclei under the extremes of angular momentum and rotational stress. Discoveries are being made which challenge our ideas of how nuclei behave.

To explore this domain further, two approaches hold promise. One is to produce high spin states in nuclei which in the past were not accessible, the other is to use more powerful and efficient instruments to detect and measure new signals which are too weak to be seen by existing devices. Thus the development of radioactive beam facilities together with the newest detector technology promise substantial qualitative expansion of the frontiers of nuclear structure research. Rapidly rotating, highly excited nuclei are produced by beams of accelerated heavy ions when a projectile nucleus collides and fuses with a target nucleus. The responses of nuclei to this rotation, which can be as fast as 10^{20} revolutions per second, are rich and varied. The crucial nuclear structure information is contained in the details of a cascade of 30 or more gamma rays emitted as each newly created nucleus, in about one billionth of a second, shakes off its excitation energy and angular momentum.

A number of preferred pathways in the deexcitation process occur. They relate to favorable arrangements of protons and neutrons and can often be associated with specific nuclear shapes. If a sufficient fraction of the decay flows down a particular pathway, then the associated structure or shape becomes observable and can be investigated in detail. In this process new and often unexpected properties of nuclei at the extremes of angular momentum and excitation energy are discovered.

Perhaps the most spectacular phenomenon in rapidly rotating nuclei has been the stabilization of very elongated nuclear shapes. These superdeformed nuclei, football-like and with a 2:1 major to minor axis ratio, possess some totally unexpected properties. Perhaps the most startling is that of identical bands. It has long been believed that the gamma-ray emission spectrum for a specific nucleus represents a unique fingerprint. However, to our great surprise, almost identical sequences of ten or more gamma-rays are seen in neighboring nuclei (see Figure I.D), not exhibiting the expected shifts from the addition of particles and the ensuing change in the moment of inertia.

An explanation of these observations as an accidental coincidence seems unlikely in view of the data shown in Figure I.7. There the observed frequency of pairs of superdeformed bands in neighboring nuclei is plotted as a function of the relative change of the moment of inertia for two mass regions: around mass A$\sim$150 (left side) and around mass A$\sim$190 (right side). Also shown for the mass A$\sim$150 (rare earth) region is the corresponding distribution for nearly 400 known normally deformed bands. The data shown represent selected subsets of all existing data as discussed in the figure caption. While the occurence of bands with very similar moments of inertia has been recognized recently in some normal deformed nuclei, it appears that, on the average, there is a distinct difference between the situation in normal and in superdeformed nuclei. The effect might be connected to the substantial differences in the strength of superfluid correlations in the two potential minima. However, the explanation of the identical band phenomenon is uncertain at this time, and may quite possibly provide a clue to a new symmetry in nuclei.

Another recent discovery in superdeformed nuclei that may suggest a new symmetry is the observation of very small but systematic shifts in the energy levels of certain bands. Levels with spins *I, I+4, I+8,...* are shifted down in energy by about 50-200 eV while the alternate levels with spins *I+2, I+6, I+10,...* are shifted up, as illustrated in Figure I.8. The long series of gamma-ray peaks with apparently regular energy spacings (see Figure I.D) are actually slightly disturbed alternately to the left and then to the right (by less than one thousandth of the gamma-ray energy) in a strange zig-zag pattern.

The two phenomena described above also demand unprecedented accuracy from theoretical calculations. These challenges are beginning to trigger new microscopic attempts to describe nuclear high-spin states and are leading to significant progress in the theoretical methods to treat the nuclear many-body system.

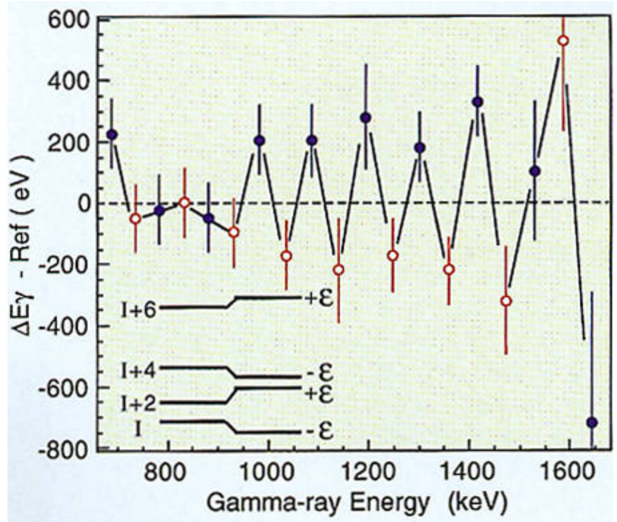

Figure I.8: Differences in energy (compared to a smooth reference) between adjacent gamma-ray lines in the superdeformed band of the ^{149}Gd nucleus as a function of gamma-ray energy. The zig-zag pattern, which represents a perturbation (ε) of about 1 part in 6000 of the transition energy, is a new feature presently not understood. One possibility is a new, four-fold geometrical (shape) symmetry.

New quantal phenomena were also found recently in nearly spherical nuclei. In the Pb isotopes, regular quasi-rotational decay sequences were found to consist of unusually strong magnetic dipole transitions (Figure I.9). This is thought to be associated with valence protons aligning their spins along the nuclear symmetry axis, and valence neutrons aligning their spins along the perpendicular axis of collective rotation. With increasing spin, the two components tilt toward each other, like the closing of shears, while the direction of the total spin remains unchanged. It is the magnetic vector, rather than the electric charge distribution, that is rotating – hence the name of magnetic rotation.

At low spins there has long been speculation, and considerable skepticism, concerning whether multi-phonon excitations – that is, superpositions of vibrational excitations – exist while preserving full collectivity. This question strikes at the heart of our understanding of the interplay of single particle and collective degrees of freedom in nuclei, and is intimately connected with the effects of the Pauli principle. Multi-phonon excitations, with nearly intact collectivity, have

Exploring the Limits

One way to study how things are put together is to hit them hard and watch what comes out of them. That, in essence, is what physicists are doing to the nuclei at the center of atoms. And with the aid of some remarkable new detection equipment, they hope to push the limits of their understanding of nuclear structure. But what may seem unusual is how physicists plan to put nuclei under enough stress that they reveal their inner secrets: by spinning them as fast as one hundred billion billion rotations per second, among other techniques.

Under such tortuous rotation, the overall shape of a nucleus as a whole may change drastically. Moderately high spins can deform the roughly spherical shape of an unspinning nucleus into a shape more like a football — with some unexpected properties. Still more highly deformed shapes have been predicted and are being sought.

A second phenomenon found in spinning nuclei is that the individual protons and neutrons that comprise a nucleus must adjust the path of their orbits within it. Just like the spin of the Earth imparts a force to air particles that help account for the circular motion of weather systems, so the spin of the nucleus tilts the orbits of protons and neutrons toward the nuclear equator — again, revealing remarkable phenomena. There is also a complex interplay between the behavior of individual nuclear particles and their collective behavior (the nucleus as a whole).

A technique often used is to collide or fuse two nuclei together to form a single compound nucleus with very high angular momentum — so much so that it gives off showers of gamma rays, reducing its excess energy and angular momentum in

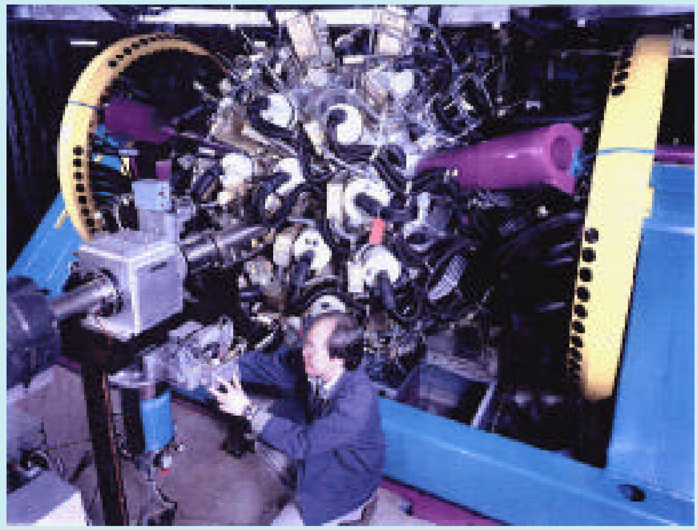

Figure I.C Gammasphere, the high resolution gamma-ray detector system for research into the structure of rapidly rotating nuclei. The facility is currently located at Lawrence Berkeley National Laboratory. Each “arm” consists of a germanium detector with a bismuth germanate scintillator shield. Most of the 110 spectrometers are installed and operating.

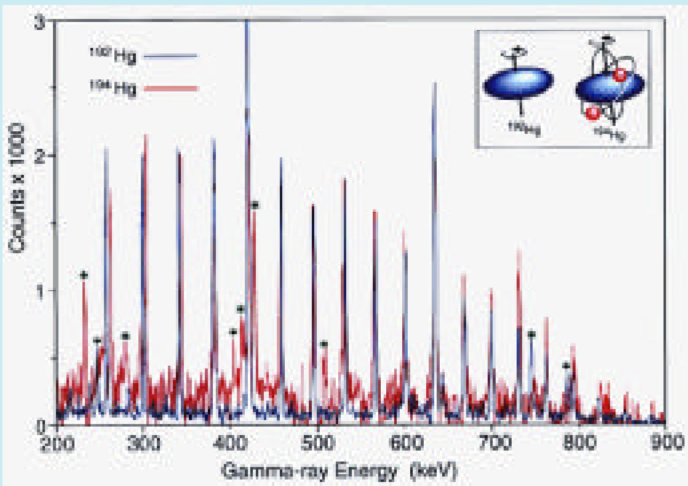

Figure I.D Gamma-ray emission patterns in two superdeformed mercury nuclei (blue and red). The very close similarity between the two "fingerprints" is unexpected and not yet understood. (Gamma-ray peaks marked with a star are not associated with a superdeformed shape.)

about a billionth of a second. Carefully observed, this cascade of gamma rays can reveal much about the structure of the severely stressed nucleus. And that is where the new detectors come in.

An individual gamma ray sensor will not see every one of these elusive radiations — they have at best a small probability of detecting a specific emission. And when they do catch one, they are then out of the game, not prepared to catch a second or a third emission in a fast-paced cascade. So modern detectors have an array of sensors. The Gammasphere instrument in the U.S., one of the newest generation of these remarkable devices, has 110 separate sensors each with improved detection probabilities over earlier sensors. The result is an advance of more than a hundredfold in the detection efficiency of a single gamma ray and thus more information on the relationships between different emissions within the cascade.

One of the phenomena that such instruments will be used to study is the curious case of matching fingerprints — identical gamma ray emission patterns — for different nuclei. Gamma ray emission patterns had long been believed to be unique to a specific nucleus, just as a fingerprint is to a human, so these identical patterns are not understood. Originally observed only in a few isolated cases, identical patterns have now been detected in a wide variety of nuclei. This proliferation suggests to physicists that the phenomenon may even represent an underlying but yet undiscovered symmetry — a potential source of deep insights into the structure of nuclear matter. Surely a sufficient motivation for pushing the limits — and spinning nuclei — even a bit harder.

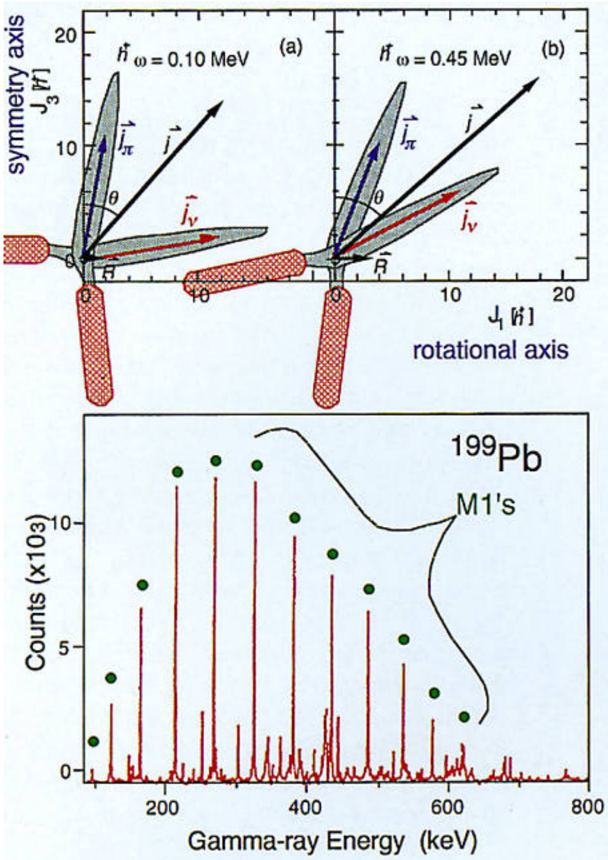

Figure I.9: A new form of quantal rotor ('magnetic rotation') has been discovered. While the gamma-ray transitions are regularly spaced as in the case of a superdeformed rotor, the character of the transition radiation is that of a magnetic dipole (M1). It is concluded that the nucleus increases its angular momentum or spin by the gradual alignment of the proton (π) and neutron (ν) spin vectors, like the closing of a pair of shears.

recently been discovered in a number of nuclei, for example ^{168}Er, ^{232}Th and ^{114}Cd.

Further advances in nuclear structure studies with gamma rays will most likely be provided by the next generation of gamma-ray detector arrays, such as GRETA (Gamma Ray Energy Tracking Array) which is described in Chapter V. This proposed array would represent a massive leap in resolving power compared to the existing systems and have a profound impact on the entire nuclear structure field. For example, one of the most important steps in understanding identical bands is to determine the exact spins of the superdeformed states. To do this one must resolve the decay pathways down to the normally deformed states, something which has not been possible with present detector systems. It is vital also to search for new nuclear shapes which inevitably illuminate new features of nuclear structure. One example is hyperdeformation which has been predicted to occur in many nuclei at the very highest spins close to the fission limit.

Order to Chaos and the Limits of Excitation Energy

The nucleus as a finite quantum system experiences striking qualitative changes as the parameters that govern its behavior are varied in a systematic way. Of particular interest is the response of the nuclear system to increasing its excitation energy. At low energy the nucleus is well described as a system of fermions at zero temperature; in an excited hot nucleus, new phenomena are expected.

For example, it now seems increasingly possible that we will be able to trace most of the path in the decay of a nucleus formed in a nuclear reaction at the fission limit down to its ground state. This offers unique capabilities to study various phenomena related to quantum chaos in the nuclear many-body environment. It is worth emphasizing that aspects of quantum chaos were first investigated by nuclear physicists in order to understand compound nuclear resonances in neutron-induced reactions. Now it has become a rather wide field of research in all areas of physics.

As the temperature in a nucleus increases a 'melting' of shell structure is expected to set in, which ultimately results in a transition from order to chaos. The recently extracted spectra connecting superdeformed and normal states in the $A{\sim}190$ mass region reveal features that suggest that the decay is the consequence of the mixing of a cold superdeformed state with a sea of hot normal states in which it is embedded. The spectra emitted at different stages of the cascade (Figure I.10) show, in sequence: (i) an unresolved hot stage feeding into the superdeformed state, (ii) sharp equally spaced lines from the cold superdeformed band, (iii) another hot stage after the decay of this band, and (iv) sharp lines in the cold cascade to the ground state. These spectra suggest a beautiful double cycle between disorder and order.

Considerable progress has also been made in identifying new, conceptually simple, modes of elementary excitation at high energies. An example is multiple excitation of the well-known giant dipole resonance (GDR).

A quantum of this excitation is visualized as the out-of phase vibration of neutrons against protons. The characteristic vibration frequency depends on the nuclear symmetry energy and the size and shape of the system. Recent experiments have succeeded in identifying states in which two such quanta are sequentially absorbed by a single nucleus (Figure I.11). The measured excitation energy is very close to twice that of the single GDR.

Unexpected changes also occur in the properties of the normal giant dipole resonance as excitation energy is added to the nuclear many-body system. It is known, for example, that the width of the ordinary GDR in highly excited (hot) nuclei increases with excitation energy. Recent experiments have demonstrated that this increase continues about linearly with temperature until, at an excitation energy of about 5 MeV per nucleon, the nucleus no longer lives long enough to support a coherent vibration. This increase in width is connected with the fact that, during its brief lifetime, the hot nucleus samples a growing number of exotic shapes as its free energy increases.

The emission of GDR photons can be used as a clock to measure stages of the decay of an excited nucleus and the timescale on which the fission process takes place. Dissipative processes in nuclei, often parameterized in terms of a viscosity, control the conversion of the deformation energy associated with fission to internal degrees of freedom; more dissipation slows fission down, producing the observed delay. It has been suggested that new results, which demonstrate a sharp increase in the fission delay as the excitation energy is increased, favor dissipation mechanisms involving collisions between the individual nucleons, as opposed to interactions of the nucleons with the boundaries of the system.

When the excitation energy per particle is of the order of the binding energy, the nucleus is expected to undergo a transition from a liquid to a gaseous state. Experimentally, the best realization of this process to date in the laboratory is through the observation of the products of collisions between heavy nuclei at velocities somewhat greater than the internal velocities of the nucleons themselves. This is discussed in Chapter III.

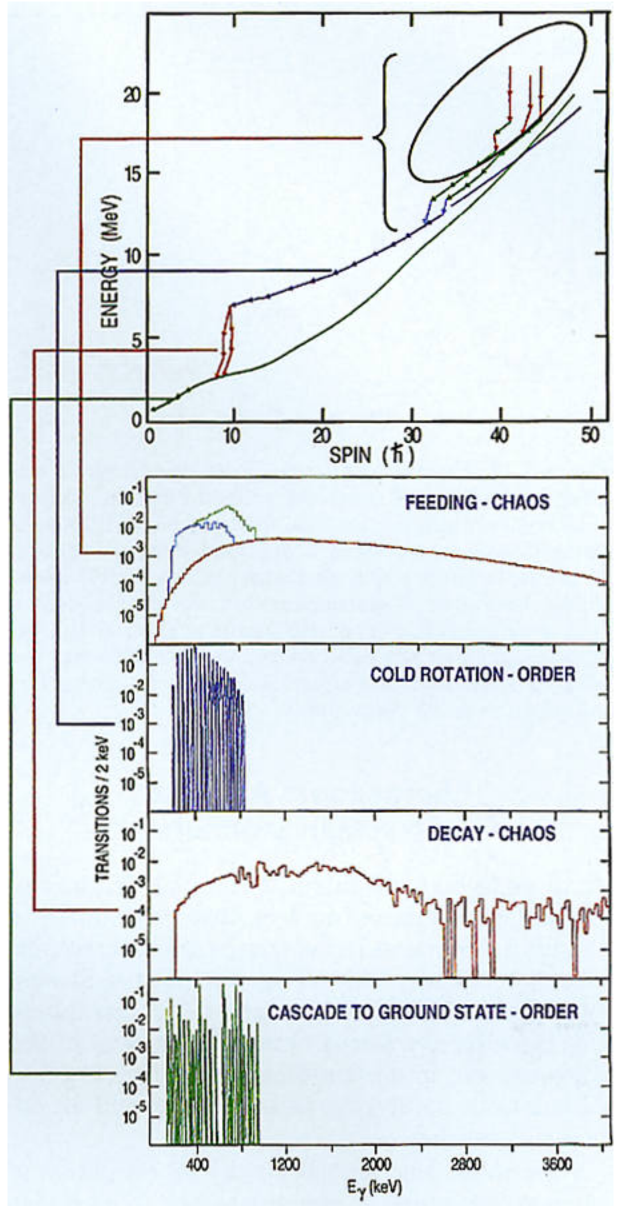

Figure I.10: The experimentally extracted gamma-ray emission spectra of the feeding and the decay of superdeformed bands. The lower four boxes display the measured spectra (color-coded) that correspond to the gamma-ray transitions shown schematically in the top figure, which the excited nucleus follows in shaking off excitation energy and spin. The data illustrate the double cycle between disorder and order, as a rapidly rotating nucleus is formed and gradually loses its angular momentum.

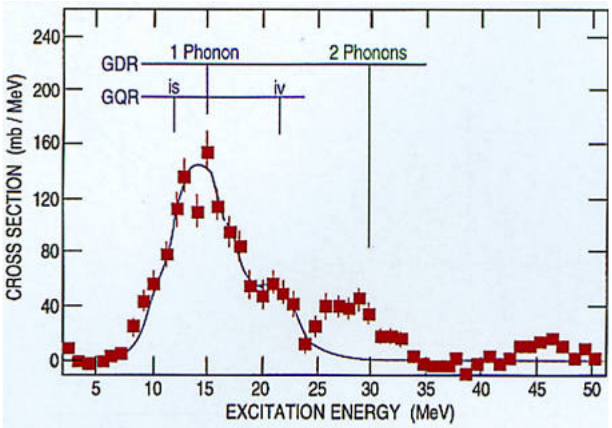

Figure I.11: Excitation energy spectrum of a xenon nucleus excited in collisions with a lead nucleus at near-relativistic energies. Intense fields of virtual photons generated in such collisions provide for the absorption of multiple quanta and excitation of the double giant dipole resonance. Evidence for this new type of excitation is seen, in the expected energy region, in the excess of data over the solid curve, which represents the contributions from the known (isoscalar and isovector) one-phonon giant resonances.

Microscopic Aspects of Nuclear Structure

As discussed at the outset of this chapter, an important component of nuclear structure studies is the effort to precisely determine the microscopic basis of nuclei. This effort includes exploring the details of the single-particle orbits, establishing the effective forces between nucleons in the nucleus, and understanding them from *ab initio* calculations involving realistic forces and all degrees of freedom.

A powerful microscope for the investigation of nuclear structure is the scattering of electrons off nuclei. The (e,e'p) coincidence reaction can reveal the wave functions of individual protons in the nucleus with high spatial resolution. The high-energy electron probe allows the dissection of the nucleus with the highest precision. Measurements at high momentum transfer trace the wave functions of strongly bound single-nucleon orbitals deep inside the massive nucleus, providing a detailed mapping of such nucleons and their properties in the nuclear medium.

Few-body systems are a particularly fruitful area for research because accurate calculations may be carried out. Comparing (e,e'p) data with these calculations tests our ability to describe nuclear systems based on an *ab initio* theory. New insights have been gained from polarization observables in electron-nucleus scattering experiments. One important result comes from recent experiments which have separated the charge monopole, charge quadrupole and magnetic dipole form factors for elastic scattering from deuterium for the first time by measuring the tensor polarization of the recoiling nucleus (see also Chapter II). The quadrupole deformation determined from this experiment (illustrated in Figure I.1) directly reflects the effects of the nucleon-nucleon tensor force. A complementary determination of the tensor force comes from low-energy transmission measurements of a polarized neutron beam through a polarized proton target. Interestingly, the tensor polarization data for elastic electron scattering from the two-nucleon deuterium system cannot be described at present by a theory that is also consistent with the measured isoscalar form factors of the three-nucleon system.

For the three-nucleon system, complete model calculations using the Fadeev equations have been refined to give predictions at low energy (typically less than 150 MeV) with accuracies generally better than two percent. The good agreement between model calculations and data validates our microscopic understanding of low-energy hadronic interactions. However, there are some puzzling discrepancies. For example, such calculations fail to reproduce the polarization data for nucleon-deuteron scattering at very low energies. These are energies that extend to below the deuteron break-up threshold, i.e., the deuteron binding energy of only 2.2 MeV. This and other discrepancies require further investigation.

Studies of polarized ^{3}He are proving to be particularly valuable for testing theoretical models and for determining electromagnetic properties of the neutron. At low momentum transfer, complete model calculations are on the horizon and promise to give new insight into the electromagnetic response of three-nucleon systems and the constituent nucleons. However, at high momentum transfer, approximations are needed to make the calculations practical. Certain aspects of reaction dynamics become less important and, for example, the electromagnetic response for quasi-elastic scattering in ^{3}He approaches that of the scattering from a free nucleon. Figure I.12 shows the results of a recent experiment which determined that at sufficiently high momentum transfer the spin observables in $^3\overrightarrow{He}(p,pn)$ quasi-elastic scattering are in good agreement with the

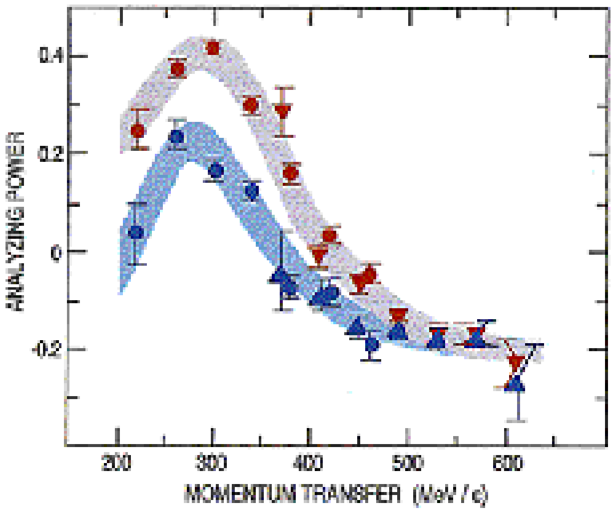

Figure I.12: Spin observables measured for quasi-elastic proton scattering from a polarized ^{3}He target. At low momentum transfer to the struck neutron, the measured analyzing powers show a distinct difference between target (blue) and beam (red) nuclei. However, at high momentum transfer they overlap and are in good agreement with the spin observables of free proton-neutron scattering. This supports the prediction that under these conditions spin observables in scattering from polarized ^{3}He are very close to those from a free neutron.

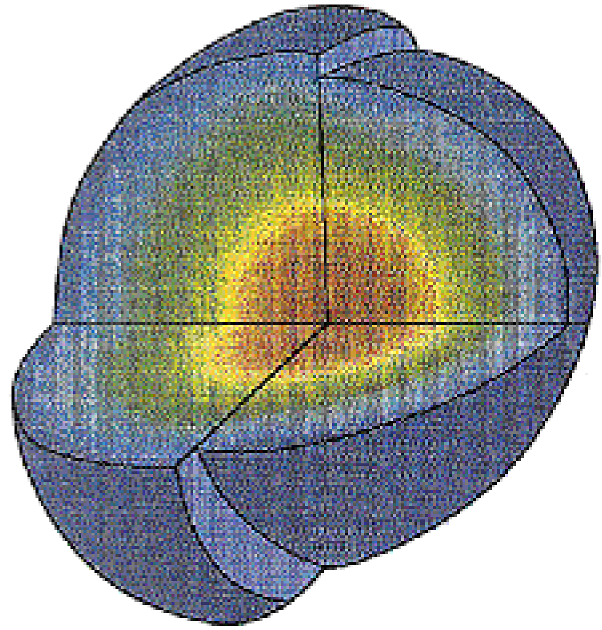

Figure I.13: Neutron (left half) and proton (right half) distributions of the ground state of ^{6}He as obtained for the first time from exact calculations based on fully realistic two- and three-body nucleon-nucleon forces.

free $p - n$ spin observables, supporting the theoretical prediction that spin observables in scattering from polarized ^{3}He are very close to those of a free neutron. At high momentum transfer the target analyzing powers measured for the $^3\overrightarrow{He}(p, 2p)$ and $^3\overrightarrow{He}(p, pn)$ reactions are in good agreement with the lowest order theoretical calculations. Related work is also carried out with photon beams.

This kind of detailed comparison of theory with data from few body nuclei over a wide range of energies and momenta is essential for our understanding of both the nucleon-nucleon potential and of nuclear dynamics. Striking progress has been made using the method of path integrals to solve the exact bound states of light nuclei. The six-body nuclei ^{6}He, ^{6}Li, and ^{6}Be have now been completely solved using realistic two- and three-body nucleon-nucleon forces. For the first time, the exact spatial distributions of neutrons and protons in the ^{6}He ground state have been calculated as illustrated in Figure I.13. Exact solutions for ^{4}He have allowed theorists to calculate the response to electrons scattered from it and to see that inclusions of all the nuclear interaction and meson exchange effects yield agreement with experimental measurements. Solutions underway for 7- and 8-body systems will provide the foundation for understanding radiative capture reactions in the Sun.

Since the discovery of the nuclear shell model, nuclear physicists have sought to solve the interactions between the nucleons in the last open shell exactly and thereby calculate the properties of medium and heavy nuclei. However, the number of states which have to be considered rendered all previous attempts intractable. Recently, by expressing this problem as the appropriate sum over path integrals which are then sampled numerically, theorists have developed essentially exact solutions of large shell-model problems. These shell-model calculations may have the potential not only to explain many aspects of nuclear structure that have been observed, but also to provide important, experimentally inaccessible, nuclear structure information for supernova dynamics and nucleosynthesis.

As detailed experiments extend our knowledge of the few-body systems to higher and higher momentum transfers, they reveal the short-range aspects of the nucleon-nucleon interaction, and probe the limit of the distance scale at which the picture of nuclear structure based on nucleon and meson degrees of freedom is valid. The structure of correlated many-body systems, particularly at distance scales small compared to the radius of the constituent nucleons, presents a formidable challenge to both experiment and theory. The quenching of single-particle strengths (relative to the predictions of the independent particle model) that has been observed at modest momentum transfers, indicates that the mean-field strength is fragmented over a large region of nuclear excitation energies. Recent studies have found that the high-momentum components of these states are significantly larger than mean field predictions. At large internal momenta, corresponding to distances <0.5 fm, effects from the exchange of heavier mesons ($\rho, \omega \ldots$) and from the internal structure of the nucleons themselves, could be important. Understanding this short-range behavior is key to many nuclear phenomena at high energies.

Finally, another dimension in nuclear structure can be studied by introducing baryons with strangeness into nuclei. These so-called hypernuclei are many-body systems composed of one or two strange baryons (such as the Λ, Σ, or Ξ, containing a strange quark) with protons and neutrons. The presence of this strangeness (flavor) degree of freedom in a hypernucleus adds a new dimension to our evolving picture of nuclear physics. It allows, in a unique way, the study of the baryon-baryon interaction in a many-body system since hypernuclei are systems of strongly-interacting particles where dynamical symmetries, forbidden in ordinary nuclei by the Pauli principle, may appear.

Summary and Outlook

Recent experiments on nuclei at the limits of stability and under extremes of motions have uncovered new and unexpected manifestations of the nuclear medium. These observations challenge our understanding of the nuclear mean-field, of the properties of the interactions of protons and neutrons submerged in the nuclear medium, and of the characterization of nuclei in the generally accepted framework of shapes, quantum states and modes of excitation. Studies of nuclei far from stability and of reactions between nuclei in unstable configurations also provide information essential for our understanding of fundamental astrophysical processes and thus are basic to a quantitative description of the energy-driven evolution of stars and nucleosynthesis.

The breadth of the field ranges from the lightest to the heaviest nuclei, from the valley of stability to the drip lines, from low to very high spin, and from tests of fundamental laws of nature to the origins and evolution of the cosmos. Major advances in theoretical calculations have been made possible by progress in computing, in particular by taking advantage of massively parallel architectures. New approaches in the evaluation and dissemination of nuclear structure data are being implemented to address needs in forefront scientific areas.

Experimental progress arises from newly developed instrumentation and capabilities. The most important future directions for this field should capitalize on new physics possibilities made possible by technical advances. Many of these arise from the opportunities with radioactive beams and will exploit the capabilities of existing and planned facilities. In addition, there are powerful new gamma-ray detectors proposed, such as GRETA, that promise to revolutionize many areas.

The nuclear physics opportunities afforded by radioactive beams open up entirely new frontiers in exotic nuclei, extending from the proton to the neutron-drip lines. Exploiting these opportunities in a comprehensive way will require both a facility with substantially improved fragmentation capabilities and an advanced ISOL facility. The genuine complementarity of the two facilities in beam species, energies, intensities, and other important parameters will allow the comprehensive and detailed investigation of nuclei far from stability. The proposed NSCL upgrade will provide large gains in intensity for higher energy radioactive beams produced by projectile fragmentation and will thus expand the region of dripline nuclei accessible to experimental investigation. The ISOL facility should produce and accelerate the broad range of intense beams of radioactive nuclei as envisioned for the benchmark facility described in the Isospin Laboratory (ISL) White Paper. That document was prepared by the ISL steering group, representing over 400 North American scientists. It provides a detailed account of the exciting science opportunities to be pursued with these new capabilities as the study of nuclear structure moves into the next millennium.

II. TO THE QUARK STRUCTURE OF MATTER

Scientific Motivation

As described in the previous chapter, we can study and understand a remarkable set of nuclear phenomena by utilizing the concept of protons and neutrons interacting through forces. However, the fundamental theory of strong interactions, quantum chromodynamics (QCD), predicts that all strongly interacting objects are actually comprised of confined quarks and gluons. Although the quarks and gluons are not observed as free unconfined particles, they are responsible for the structure and interactions of all strongly interacting systems. Therefore, understanding the underlying mechanisms responsible for the properties of nuclear matter and the forces that govern its behavior requires that we expand our view to include the quark structure of matter.

QCD is one component of the highly successful and well-tested Standard Model unifying the strong, electromagnetic, and weak forces observed in Nature. QCD describes the interactions between quarks via the exchange of gluons and provides the foundation for understanding the properties of nucleons, nuclei, and other particles collectively known has hadrons. This is similar to the way that quantum electrodynamics (QED) describes the interactions between electrons via photon exchange and provides the basis for our understanding of atoms, molecules, and solids. Unlike photons, however, the gluons of QCD are self-interacting with the result that the interaction between quarks gets stronger as they get further apart. This behavior gives rise to the striking phenomenon of confinement: unlike an electron which can be removed from an atom, quarks do not exist as free particles outside of hadrons.

The quark/gluon structure of hadrons can be directly observed by probing the system at very high energies where the quark and gluon interactions are weaker and can be calculated using QCD. However, at lower energies the nature of QCD is much more complex and there is no completely successful mathematical framework for applying the theory. In this regime, a common approach has been to develop effective theories to approximate QCD. One very successful strategy has been to describe the structure and interactions of hadrons using composite objects. For example, nucleons and their close relatives known as baryons have many properties that are explained using “constituent quarks”, which are actually composite objects containing quarks, antiquarks and gluons. Another important and very successful example involves the force between nucleons and other baryons where the exchange of mesons provides an excellent description over a broad range of energies. Understanding these phenomenological treatments within the context of QCD and the further development of new methods to approximate QCD at low energies are basic and important goals of modern nuclear physics.

Recently theorists have made much progress in developing a theory that exploits an approximate symmetry of QCD, known as chiral symmetry, to provide a low energy description of hadronic forces. Chiral symmetry is due to the fact that the lightest quarks, known as up and down quarks, both have very small mass. This symmetry is spontaneously broken in nature, which gives rise to the existence of the lightest meson, the pion. This property allows one to develop a systematic treatment of hadronic forces, known as chiral perturbation theory, where the low energy behavior is characterized by just a few parameters which can be determined by experiment. There has been a great deal of recent progress in successfully describing a wide variety of low energy experimental results using this technique.

Another approach, which is becoming extremely powerful with emerging computer technology, is the numerical solution of QCD on a discrete space-time lattice. A major accomplishment over the past few years has been the successful calculation of a broad range of hadron properties in an approximation which neglects certain effects of the sea of quarks and antiquarks which are present in hadrons. Recent theoretical developments and advanced computer technology now provide the means to include these omitted dynamical effects and obtain a more complete (and thereby more accurate) solution of QCD

Thus, QCD and the physics of confinement pose many challenges which lie at the heart of modern nuclear physics. Future progress requires the study of all forms of hadronic matter, spanning the complete range of energies that are necessary to probe the quarks and gluons directly as well as elucidate the properties of confined systems. This includes mesons, baryons, and their interactions as well as more complex objects such has heavy nuclei. As demonstrated in the remainder of this chapter, a wide variety of facilities and activities are required to provide crucially important input in many areas. In particular, the new large facilities, CEBAF and RHIC, are expected to provide definitive new information on complementary aspects of this subject.

The Structure of Nucleons and Related Hadrons

Just as the few-nucleon system provides the best environment to study elementary aspects of the behavior of more complex nuclei, studies of the internal structure of nucleons and other relatively simple hadrons are an essential stepping-stone towards understanding more complex forms of hadronic matter. In QCD, the description of nucleons and other hadrons involves quarks, gluons, and a sea of quark-antiquark pairs ($q\bar{q}$). The quarks can be any of six different "flavors", and one can form related types of hadrons by interchanging the flavors of the quarks. For example, the nucleon is made of primarily up and down quarks and one can make other related baryons by replacing one of the quarks with a strange quark.

The $q\bar{q}$ sea represents an important aspect of hadronic structure, and the study of the sea has become an integral part of our attempt to understand hadronic structure quantitatively within the framework of QCD. In recent years, we have seen dramatic progress in the development of the theoretical description of the $q\bar{q}$ sea of the nucleon. Experimental data from deep inelastic scattering have played a key role in guiding these advances and vigorous new experimental efforts are underway. These experiments promise to shed new light on basic issues regarding the origin of the nucleon spin as well as the flavor composition of the sea, particularly the role of strange quarks.

Recent polarization measurements in deep inelastic electron and muon scattering from the nucleon indicate that the fraction of nucleon spin carried by the quarks is significantly smaller than expected in the constituent quark picture. In fact, less than one-third of the proton's spin seems to be carried by the quarks. The remainder is apparently contained in the spin of the gluons and orbital motion of the quarks and gluons.

Due largely to innovative developments in spin-polarized ^{3}He and deuterium targets the spin structure function of the neutron was recently measured for the first time. This permitted a test of a fundamental prediction of QCD (known as the Bjorken sum rule) for the difference between the integrated proton and neutron spin distributions. The recent data are in fact consistent with the Bjorken sum rule value predicted by QCD, and provide further confirmation that QCD is correct.

However, the unexpected small amount of spin carried by the quarks has motivated further studies to elucidate the origin of the spin of the nucleon. In particular, measurement of the momentum-transfer dependence of the spin structure would be sensitive to the gluon polarization and determining the flavor composition would provide crucial additional information on the quark spin structure. A potentially powerful method for determining the quark flavor contribution to the spin structure of the nucleon is to "tag" the flavor of the struck quark by identifying the hadron emerging from the deep inelastic scattering event. Coincident kaon or pion detection should permit determination of the separate spin contributions of the up, down, and strange quarks (and antiquarks). This technique will be utilized by the HERMES experiment at DESY in the near future.

The polarization of the antiquark sea in the proton can be probed using the annihilation of a quark in an incoming polarized proton with an antiquark in a polarized target proton. In addition, the effect of gluons on the proton's spin can be studied in future measurements of direct photon production from collisions of polarized protons. These experiments would make use of the polarization capabilities at RHIC and FNAL.

Another surprising property of the sea was revealed by measuring the relative amount of $\bar{u}$ (anti- up quarks) and $\bar{d}$ (anti- down quarks) in the nucleon. New measurements of deep inelastic muon scattering from CERN have demonstrated that there is a substantial difference in the relative number of $\bar{u}$ and $\bar{d}$. Recent theoretical work indicates that this may be due to the presence of pion fluctuations in the nucleon and may help establish a link between the $\bar{q}q$ sea of the nucleon and the role of pions in nucleon structure.

More recently, the relative amount of $\bar{u}$ and $\bar{d}$ has been studied at CERN via production of muon pairs (from the annihilation of quarks and antiquarks) in high energy proton−proton and proton−deuteron collisions. The result appears consistent with the $\bar{u}$-$\bar{d}$ difference seen in deep inelastic scattering scattering. A new experiment at Fermilab will measure muon pair production to study the ratio $\bar{u}/\bar{d}$ with better precision over a wider kinematic range and provide more detailed information on the sea quark distributions.

At lower energies, the $\bar{q}q$ sea can manifest itself through the role of pions and their effects on hadronic structure and interactions. For example, the role of pions in nucleon structure has been revealed in recent measurements of a fundamental low energy property of the nucleon: the "polarizability". In response to electric and magnetic fields, the distribution of charges associated with the quarks and antiquarks is distorted leading to the property known as "polarizability". The results of recent experiments are displayed in Figure II.1; they clearly indicate that one must include the fluctuations to excited nucleon states such as the Δ in addition to pionic effects. In particular, these polarizability measurements demonstrate that nucleon excitation effects can and must be included in the chiral perturbation theory treatment of hadronic interactions.

The unperturbed distribution of charged quarks and antiquarks in the nucleon can be determined by measuring the electromagnetic form factors in electron scattering. These form factors can be compared with various theoretical calculations to test our understanding of nucleon structure. They are also important in the interpretation of the distribution of strange quarks in the nucleon and precision studies of few-nucleon systems (both discussed later in this chapter). New and powerful techniques have recently been developed which are particularly useful in measurements of the electric and magnetic form factors of the neutron (G_E^n and G_M^n). These new methods involve the use of polarized electron scattering in concert with either polarized targets (^{3}He or D) or a recoil neutron polarimeter. Recent pioneering efforts have demonstrated the power of these experimental techniques by providing precise new data on these form factors. These measurements indicate that future experiments at CEBAF and other labs will finally provide definitive and precise information on these important quantities.

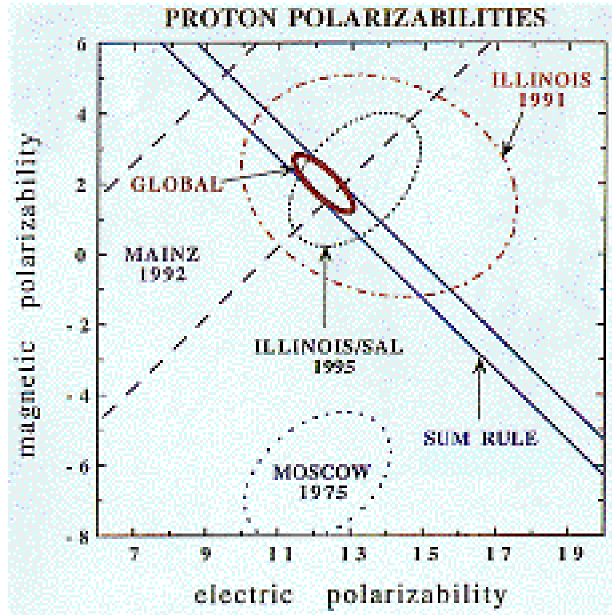

Figure II.1: Various experimental determinations of the proton's electric (α) and magnetic (β) polarizabilities. The region labelled "global" is the combined region allowed by the recent experiments and now represents a precise enough determination to demonstrate the role of excited nucleon states.

As discussed above, spin-dependent deep inelastic scattering data may suggest that strange quark antiquark pairs ($s\bar{s}$) play a significant role in the quark spin structure of the nucleon. In addition, analyses of low energy pion scattering data indicate that $s\bar{s}$ pairs may contribute a significant amount to the nucleon mass. These studies have motivated a new program to explore the role of $s\bar{s}$ in other nucleon properties such as the magnetic moment and the electric charge distribution. These new experiments include both studies of parity violating electron scattering and low energy neutrino-proton scattering; they will enable separation of the contributions of up, down, and strange quarks to various properties of the nucleon.

Two experiments are presently underway. The LSND experiment at LAMPF will measure the ratio of neutrino-proton to neutrino-neutron cross sections at low energy and determine the strange-quark contribution to the nucleon spin; this will provide very important complemen-

Where Does the Proton Get Its Spin?

Protons, the nuclei at the heart of hydrogen atoms and one of the main constituents in nuclei at the center of more complex atoms, have “spin”. If they didn’t, the lifesaving diagnostic technique of Magnetic Resonance Imaging (MRI) would not work. Spin is intimately associated with the origin of a proton’s magnetism — just as the Earth’s rotation is related to the origins of its magnetic field. It is the magnetism of protons and neutrons, and hence that of nuclei, that gives an MRI scanner its diagnostic power. The scanner uses a strong magnetic field and radio waves to interact with the tiny nuclear magnets in human tissue and thus to detect abnormalities non-invasively.

So where does the proton get its spin? To the consternation of physicists, they have been unable to explain this spin in terms of the proton’s constituents — the quarks, antiquarks and gluons confined within. The spin of the constituents, together with that generated by their orbital motions, must add exactly to the spin of the proton. Physicists set out to determine the balance using high energy accelerators much like gigantic electron microscopes and using new techniques which line up the spin in the electron beams and in the target protons. They were shocked by the initial result — when added together, the spins of all the quarks and antiquarks cancel nearly completely. Even with more accurate recent experiments at the Stanford Linear Accelerator Center and at the CERN Laboratory in Geneva, only one third of the proton’s spin is found in the quark and antiquark spins. It had been expected that most of the proton’s spin would reside there.

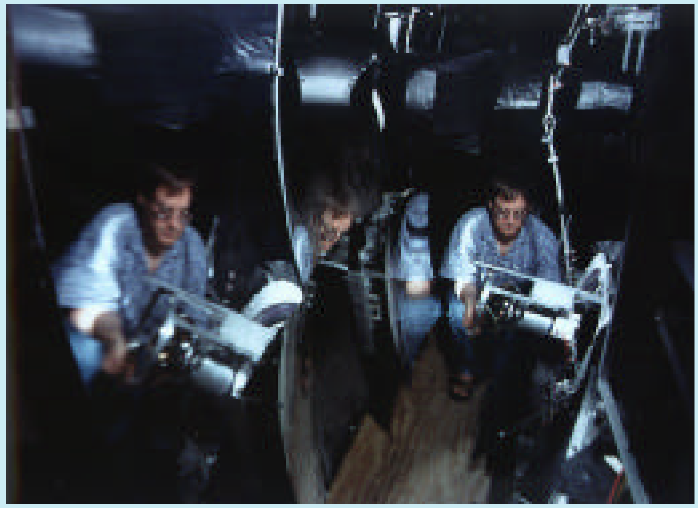

Figure II.A Large photomultiplier for the Cherenkov detector of the SAMPLE experiment at MIT/Bates is examined by Caltech graduate student Bryon Mueller. His image is also seen in the mirrors which are used to reflect light to the photomultiplier.

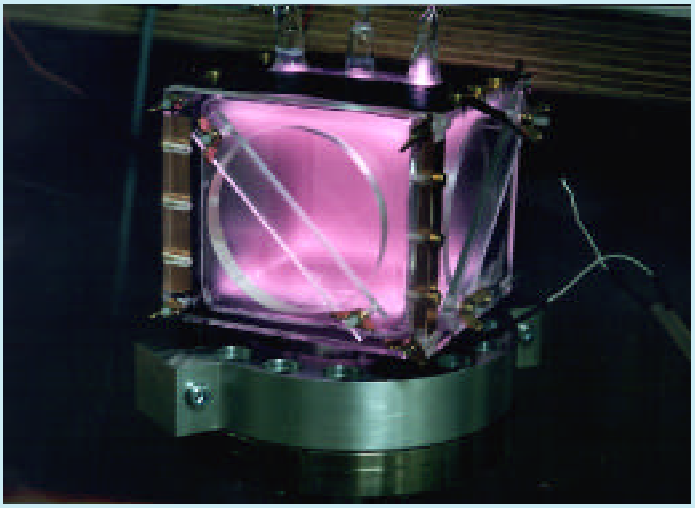

Figure II.B Optical pumping cell for the polarized ^{3}He target recently developed by nuclear physicists at MIT and CalTech. It is being used in the HERMES experiment at DESY to study the quark spin structure of the neutron. The helium gas is glowing purple due to a discharge maintained in the cell to facilitate polarization by laser light.

The “spin crisis” remains puzzling and will be the focus of an intense assault by nuclear and particle physicists over the next several years. Novel experiments will try to separate the spin contributions of different types of quarks and antiquarks, of gluons, and of orbital motion. For example, the HERMES experiment in Germany, where U.S. physicists are collaborating with those from several other countries, will use polarized nuclei, such as ^{3}He, inside the large HERA electron accelerator and will identify different types of quark constituents. Experiments using high energy proton beams (also with the spins lined up!) at the new RHIC facility will clarify the level of gluon contributions. And complementary experiments at much lower energies, those underway at MIT and planned for CEBAF, will measure the proton’s magnetism arising from strange quarks. These last experiments rely on the lack of perfect mirror symmetry in nature, leading to a tiny difference in the interaction of electrons with protons when the electron spin direction is reversed. When these programs are completed, we should have a clear picture of how the proton gets its spin.

All of the experiments, driven by the fundamental physics issue of understanding the proton’s and neutron’s magnetism, require demanding new technology. It is intriguing that (as discussed in Chapter VIII) some of this new technology, the development of polarized ^{3}He nuclei, is in turn opening up entirely new vistas for MRI clinical diagnostics. The decades-old quest to understand nuclear magnetism at progressively deeper levels will continue to reward our efforts with deeper insights into the structure of matter and practical consequences as well.

tary information to the deep-inelastic scattering experiments. The SAMPLE experiment at MIT/Bates will measure the parity violating component of elastic electron-proton scattering at very low momentum transfers. This measurement will determine the contributions of the individual u, d and s quarks to the magnetic moment of the proton. Similar measurements on the deuteron will help reduce theoretical uncertainties and thus improve the reliability and precision of the determination of the strange quark contribution to the proton's magnetic moment. Additional parity violating electron scattering experiments aimed at exploring the strange sea contributions to the charge and magnetization distributions of the nucleon over a wide range of momentum transfer represent one of the highest priority programs at CEBAF.

The structure of the nucleon can be further tested by observing the effects associated with adding energy to the system. When struck by another particle, the constituents of the proton and neutron can be knocked into new excited "orbits", much as is the case for ordinary atoms. The study of the resulting quantum levels is a tool used in both atomic and nuclear physics to expose two key features of any such system: the nature of the constituents and the forces between them. The existing fragmentary knowledge of the excited states of the nucleon suggests that they can be approximately described as three "constituent quarks" in orbit around each other. (One should keep in mind that these constituent quarks are actually composite structures made of the quarks, antiquarks and gluons probed in the deep inelastic scattering experiments discussed above.) To test this picture further, it is essential to improve on our rather limited knowledge of the nucleon spectrum. For example, one must search for excitations in which at least two of the quarks are excited simultaneously (none are known at this time). Another important example involves the production of the first and best known nucleon excitation, called the Δ, which is produced by flipping over the spin of one of the three constituent quarks in the proton so that all three spins are aligned. Many calculations predict that this state is non-spherical, and one can measure this property using polarized electron and photon beams to study this excitation. In fact, recent experiments using photons to excite the nucleon already indicate that the Δ is, in fact, non-spherical.

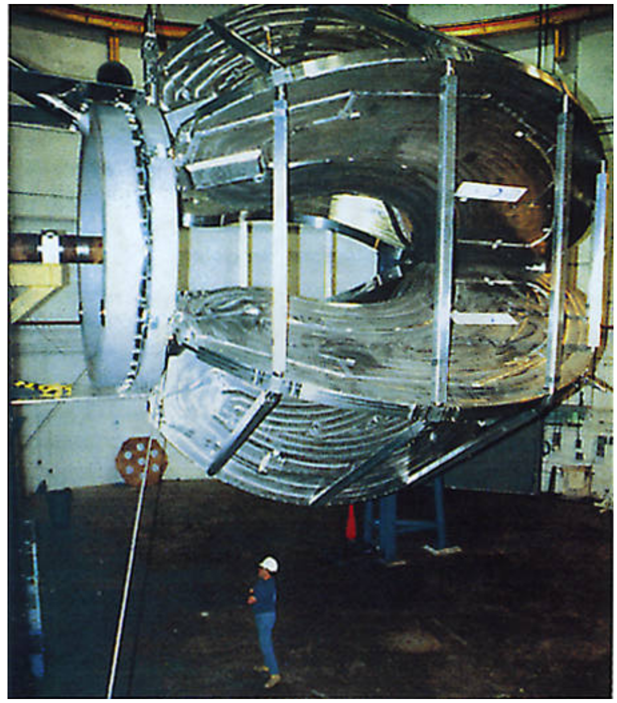

Figure II.2: The CLAS detector is presently under construction at CEBAF. When complete, this instrument will be a powerful new tool for the study of the properties of nucleon excitations and many other physics topics.

The discovery and study of new excited nucleon states which cannot be explained by the constituent quark model would address interesting questions such as whether the gluons inside the proton are frozen out into narrow string-like structures (as suggested by the so-called "flux tube models"), or appear as a confining field surrounding the quarks (the "bag model"). These studies of the excited states of the proton must be complemented by exploration of exotic structures in another arena: that of the mesons.

Meson Spectroscopy and Structure

Unlike the baryons, which seem to be built of three constituent quarks, the mesons are potentially simpler objects built of a constituent quark-antiquark pair. In many cases the simplicity of the latter systems makes them preferable as testing grounds for our understanding of strongly interacting matter. In the constituent quark picture, only mesons with certain combinations of spin and reflection symmetry ("parity") are predicted to exist. Therefore, it is often easier to unambiguously identify novel types of mesons than of baryons. In particular, it is expected that some of the first gluonic excitations of mesons will have exotic spin-parity combinations that are not allowed in the constituent quark picture. Experiments to find such particles are planned both for CEBAF, exploiting its ability to exceed its design energy of 4 GeV, and for various hadron beam facilities.

In addition to the excitation of the gluons within mesons and baryons, QCD also indicates that a totally new kind of quarkless strongly-interacting matter could exist: “glueballs”. Lattice QCD has recently been able to provide guidance on the mass and expected properties of such states, and nuclear physicists are actively engaged in searches for them. It is not expected that easily identified glueballs will exist at lower energies so a variety of methods must be employed to establish this important property of QCD.

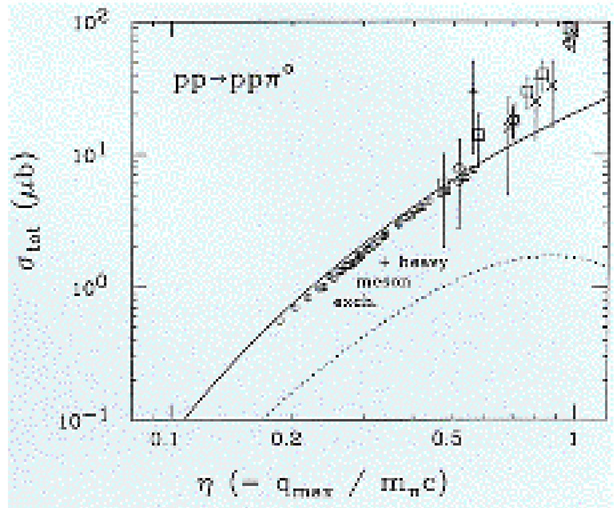

Figure II.3: Recent IUCF data (small open circles) on threshold π^0 meson production in pp collisions along with theoretical curves which include (solid line) or exclude (dashed line) the effects of heavy meson exchange.

Hadronic Interactions

Atomic nuclei, nuclear matter at high density, and neutron stars are examples of systems containing many interacting hadrons in close proximity. It is essential to understand the strong force between pairs of hadrons in order to treat these many-body systems. In such systems the hadronic interaction distances are typically about the same as the confinement scale that governs the size of the hadrons, and the interaction becomes much more complex: QCD phenomenology indicates that numerous quarks and gluons may be exchanged.

At relatively large distances (compared to the confinement scale) it is well established that pion exchange provides an excellent description of the force between nucleons. At shorter distances, this force has been rather successfully described by the exchange of heavier mesons, such as the ρ or ω, and of multiple pions. It is important to determine where this picture breaks down and a description in terms of quarks and gluons becomes more appropriate. A prominent recent success of meson-exchange models is shown in Figure II.3, comparing measurements and calculations of the cross section for production of a single π^0 meson in pp collisions very near the production threshold. Dramatic improvements in the quality of data attainable so close to threshold have been made possible by use of stored, cooled proton beams and an ultra-thin hydrogen gas jet target at the IUCF Cooler. In this regime, the process appears to be dominated by contributions involving the exchange of heavy mesons between the interacting nucleons. The experimental results are well-reproduced by calculations which fix the heavy meson properties to values obtained by fitting elastic NN scattering data.

Another test of the heavy meson exchange picture at short distances involves measurement of the property of “charge symmetry”. A system is described as displaying “charge symmetry” if its properties are unchanged when the up quarks are replaced by down quarks and vice versa. The small violation of charge symmetry in the strong nuclear force has been clearly demonstrated in recent precise measurements of elastic scattering of polarized neutrons by polarized protons, and in π-deuteron scattering. The elastic n-p results, along with other nuclear manifestations of charge symmetry breaking, are inconsistent with recent calculations involving the exchange of mesons between the nucleons. Important additional information will be provided by future experiments probing charge-symmetry-violations in the forces between other pairs of mesons or baryons.

The meson-exchanges between nucleons can be directly studied in electromagnetic studies of the structure of light nuclei, where a photon can interact with one of the mesons “in flight.” This process has been used with great success for many years to elucidate the meson-exchange picture of interacting nucleons. Recently, the

A Microscope for Nuclear Matter

After a decade of construction, the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, VA, has just begun its long-awaited program of experiments in nuclear physics. A principal focus of CEBAF's research is exploring and understanding the underlying quark structure of matter.

Since the discovery of the atomic nucleus in 1911, scientists have been searching for an understanding of the force which binds matter into nuclear sizes (a millionth of the size of an atom). By mid-century, it was believed that the binding resulted from the strong force observed between the nuclear constituents, the proton and the neutron. Since then, our understanding has undergone a profound transformation: we now know that *quarks* and *gluons* — not protons and neutrons — are, along with electrons and photons, the basic building blocks of the world we see around us. This discovery gives nuclear physics a basis as solid as the electromagnetic theory on which atomic and molecular physics are built. The analogy is deep: the proton and neutron are now known to be quark "atoms" (bound states of quarks held together by the strong force generated by the gluons) just as ordinary atoms consist of electrons bound to the atomic nucleus by electromagnetism (the force generated by the photons). Nuclei are analogous to molecules, both being relatively weakly-bound compounds of their respective "atoms." Indeed, we now know that the forces between protons and neutrons, once supposed to be the strong force, are only a weak residue of the inter-quark forces, analogous to the weak molecular forces that arise from the fringe fields of atoms. However, our understanding of exactly how these nuclear "atoms" and "molecules" are constructed from their quark and gluon constituents is rudimentary at best, and solving this puzzle is one of the greatest challenges facing nuclear physics.

Figure II.C The world's largest assembly of superconducting accelerator cavities, cooled by a refrigerator that doubled the world's supply of helium at 2 degrees kelvin, are an essential element in the production of CEBAF's continuous electron beams.

Figure II.D Aerial view of the recently completed Continuous Electron Beam Accelerator Facility (CEBAF). The electron beam traverses the mile-long, racetrack-shaped accelerator as many as five times, reaching an energy of 4 billion electron volts, and is then directed to the three large experimental halls buried under the circular domes visible in the foreground. The large building in the center of the racetrack houses the helium refrigerator.

The beams produced at CEBAF are uniquely suited for elucidating this problem. The accelerator and its experimental equipment provide an electron microscope optimized to "see" objects ranging in size from a large nucleus down to about one-tenth the diameter of a proton. Because CEBAF's beams are continuous in time, previously impossible experiments can be carried out. For example, we can use an electron to transfer energy to a quark in a proton, exciting the proton to one of its "atomic" levels, and then observe the complex de-excitation (or decay) of this excited state. This capability is critical for the study of proton and neutron "atoms" because the strength of the interactions is so great that their excited states overlap, requiring highly sophisticated experiments to even identify the different states. Just as ordinary spectroscopy proved to be the incisive tool for understanding the electronic structure of atoms, proton and neutron spectroscopy will reveal many basic features of the quark structure of matter and provide a critical testing ground for quark models attempting to describe these systems.

With a basic understanding of the proton and neutron in hand, it will also be possible to finally place our understanding of the atomic nucleus on a firm foundation. This understanding is now largely based on empirical models analogous to early pictures of molecules in which the atoms were treated as elementary subunits. This picture must break down when the quark structures of the protons and neutrons in the nucleus overlap.

CEBAF's focus places it on the border between traditional nuclear and high energy physics. It will be one of the world's leading laboratories in the effort to bridge the gap between the underlying quark and gluon theory and the world we see around us.

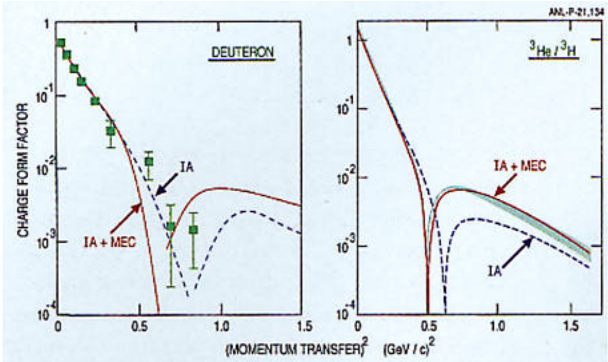

Figure II.4: Recent data on isoscalar charge form factors in the (a) deuteron, and (b) the $A = 3$ system. While the $A = 3$ data favor the inclusion of meson exchange currents (MEC) in addition to the Impulse Approximation (IA), the deuteron data seem to favor a lack of MEC.

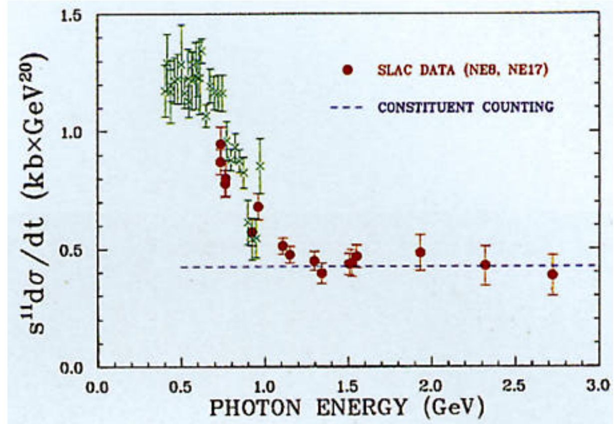

Figure II.5: The recent SLAC data on deuteron photodisintegration are consistent with the constituent counting rules as predicted by perturbative QCD arguments.

sensitivity of such experiments to the details of the meson exchange picture has been enhanced by the addition of polarization measurements. For example, polarization measurements of elastic electron-deuteron scattering have allowed, for the first time, the determination of the distribution of charge within a deuteron at short distances, as small as 1/5 fm. As shown in Figure II.4, these new data are not reproduced by calculations incorporating meson exchange currents, although analogous calculations had previously met with great success in reproducing charge form factors for mass-3 nuclei. Additional polarization measurements for the deuteron, planned at CEBAF to extend to higher momentum transfer, are needed to clarify this discrepancy.

At higher energies, there is already evidence that some behavior characteristic of hard QCD interactions sets in when photons are used to decompose a deuteron into a neutron and proton. Recent results from SLAC for this reaction, shown in Figure II.5, reveal an energy dependence that agrees well with simple "counting rules" based on the total number of point-like constituents (here, valence quarks and the photon itself) participating in the interaction. Future experiments at CEBAF will provide crucial information on whether this behavior persists in polarization measurements.

In order to explore the short-range hadronic force, it is also important to make measurements for pairs of baryons other than two nucleons. There are two basic advantages to these complementary systems: symmetry constraints may reduce or eliminate the role of one pion exchange; the short-range interaction may be much less strongly repulsive (or even attractive) than it is in the two-nucleon system. For example, the Λ is a baryon nearly identical to the neutron except a strange quark has replaced a down quark. Single pion exchange should be absent from the interaction between two Λ's or between the Λ and a nucleon. Standard meson-exchange potential models have been extended to ΛN and $\Lambda\Lambda$ systems, but they are presently poorly constrained due to a lack of experimental data. A variety of experimental programs are in place or being planned to improve substantially our knowledge of these systems. One should also note in this context that the study of nuclei containing two Λ's will provide a gateway to the study of multiply strange hadronic or quark matter in high energy heavy ion reactions at the AGS and RHIC.

Nuclei containing one or more Λ particles are examples of hypernuclei. Hypernuclei allow unique investigations of the weak interaction between a Λ and a nucleon. This interaction can transform the Λ-N system into two nucleons. There is a clear distinction between meson-exchange and quark model predictions for the relative strengths of the weak Λ-neutron and Λ-proton interactions that can be addressed using, for example, the reaction $^4\mathrm{He}(\mathrm{K}^-, \pi^0)^4_\Lambda\mathrm{H}$.

Another way in which two-baryon systems can permit critical tests of meson-exchange *vs.* quark models involves a system of two Δ particles. In contrast to the short range repulsion one finds in the N-N force, quark models predict short-range attraction, and hence, strong spatial overlap, of two Δ particles under certain conditions. It may be possible to produce two Δ's and to select the appropriate state for investigation either in collisions of polarized deuteron beams with a deuterium target or in pion double charge exchange from $A = 3$ nuclei.

Just as the structure of mesons provides crucial information beyond that obtained from baryon structure, it is also important to study the interactions between mesons. For example, the interaction between two pions at low energies is sensitive to chiral symmetry breaking, and is a fundamental aspect of chiral perturbation theory. New experiments aiming to produce a novel "atom" comprised of a positive and negative pion can provide precise information on the strong force between pions at very low energies.

Hadrons in Nuclear Matter

Since nuclear matter consists of strongly-interacting hadrons in rather close proximity, it is highly likely that hadrons (which are composite objects) have a modified internal structure in a nucleus relative to what they have in free space. However the existing experimental evidence and theoretical interpretation indicate the changes are small at normal nuclear matter density. What does happen to a hadron in the nuclear medium? This is a fundamental question which may be related to some of the longest standing open issues in nuclear physics.

At the quark level, measurements at high energies clearly demonstrate that the quark structure of the nucleus is different than that of an unbound collection of protons and neutrons. One striking example occurs when a single quark in a nucleus carries, for a short time, the momentum of more than one nucleon; this process is sensitive to the clustering of nucleons into 6, 9, 12 .. quark objects and the short-distance correlations between nucleons in the nucleus. However, when we measure the antiquark distributions and the total fraction of the momentum of the nucleus carried by the quarks these remain the same as in a free proton. In the future, it is important to explore the contributions of the different quark flavors in nuclei ($u, \bar{u}, d, \bar{d}, s, \bar{s}, c$...) and make definitive measurements of the nuclear gluon distributions. One should also note that knowledge of quark/gluon distributions in nuclear media are of fundamental importance in understanding the early stages of relativistic heavy ion collisions.

Many theoretical approaches to non-perturbative QCD imply that hadron structure should change as a function of nuclear density. For example, both QCD sum rules and the limit of QCD with a large number of colors predict that at nuclear densities the mass of the nucleon will be reduced significantly. Similar analyses predict that the vector mesons like the ρ, ω, and ϕ should also have reduced masses. This can have a significant effect on that part of the force between two nucleons which arises from the exchange of these mesons and so may have implications for nuclear structure. A related question is: what happens to the pion field in the nucleus? The forces between nucleons in nuclear matter could lead to an enhancement of the number of pions in nuclei relative to free nucleons. Yet measurements of antiquark distributions indicate that the pion field of the nucleus is essentially the same as that of the free nucleon. Critical direct searches for these and other changes can be performed with electromagnetic and hadronic probes in normal nuclear matter and with relativistic heavy ions at higher densities.

Another important effect involves the role of QCD in the quantum evolution of fast hadrons as they travel through nuclear material. While a normal hadron has an average radius of $\sim 0.5 - 1$ fm, it contains fluctuations which are much smaller in size. Since the color force between this hadron and other hadrons in a nucleus depends on the magnitude of separation of color, such small-size hadronic fluctuations will interact weakly with nuclear matter and pass relatively easily through it, a phenomenon known as color transparency.

We can test this prediction by using a reaction that we know forms small-sized states like vector meson production at high energies. As shown in Figure II.6, recent measurements of ρ-meson production at FNAL and CERN show tantalizing hints that nuclei may become more transparent in this reaction. A proton-proton scattering experiment at high momentum transfer at the AGS also shows possible color transparency effects. However, recent data on proton knockout using a high energy electron beam at SLAC seem to show no evidence for increased transparency (see Figure II.6). These reactions must be pursued to higher energies to clarify the situation. In addition, further measurements of the production of ρ-mesons and other vector mesons in nuclear systems are required. It is of fundamental importance to measure the onset of transparency

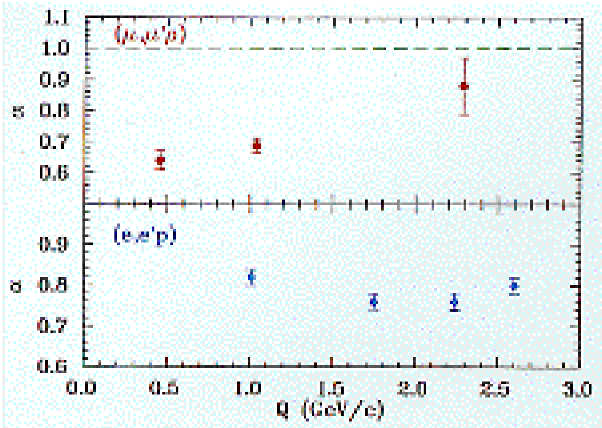

Figure II.6: Recent data on $(\mu, \mu'\rho)$ and $(e, e'p)$ for various nuclei as a function of momentum transfer. The transparency of the nucleus consisting of A nucleons is parametrized by $A^{(\alpha-1)}$, so that perfectly transparent nuclear matter corresponds to $\alpha = 1$. While the ρ production data indicate an increase in nuclear transparency at higher momentum transfers, the $(e, e'p)$ data do not show this effect.

effects in these and other experiments in order to understand fully this remarkable phenomenon in nuclear QCD.

In summary, there has been much recent progress in pushing our knowledge of strongly interacting matter to shorter distances using various aspects of the fundamental theory, QCD. New experimental programs are in place to further our quest for decisive answers to basic questions such as the role of heavy meson exchange in nuclear forces, the contribution of strange quark-antiquark pairs to the structure of nucleons and nuclei, and the origin of the spin of the proton. The projected results of these experimental programs coupled with the expected progress in theoretical treatments of non-perturbative QCD offer the promise of an exciting and enlightening future in our endeavor to understand the nature of strongly interacting matter in terms of the fundamental building blocks of QCD.

III. THE PHASES OF NUCLEAR MATTER

Scientific Goals and Motivation

Probing the QCD vacuum

As has been described earlier, the Standard Model of elementary particles and their interactions asserts that the fundamental constituents of nuclear matter are quarks and gluons. Yet, no quark or gluon has ever been seen in isolation. They are always found confined in composite particles, such as nucleons and mesons, which have neither the color charge nor the approximate chiral symmetry possessed by nearly massless quarks. To gain an understanding of why and how the fundamental chiral symmetry is broken and the color charge of quarks and gluons is hidden from observation is one of the important objectives of modern nuclear physics.

The most likely resolution of these puzzles appears to lie in the complex structure of the physical vacuum itself. Condensates of gluons and quark-antiquark pairs in the physical vacuum (similar to the Cooper pair condensate of electrons in a superconductor) may be responsible for the complete suppression of color electric fields and the breaking of the chiral flavor symmetry. In this picture, the vacuum paradoxically is far from being devoid of structure and must be regarded as a complex physical medium.

In order to probe the structure of the physical vacuum it is necessary to perturb it with sufficient excitation energy to dissolve the condensates over space and time distance scales which are large compared to those characteristic of the condensates. Calculations based on quantum chromodynamics (QCD) predict that the temperature scale required is $T_c^{(QCD)} \approx 150\ MeV$ or $10^{12}\ K$, as indicated in Figure III.1. This corresponds to an energy density in excess of 1 GeV/fm^3, or more than seven times the average energy density inside atomic nuclei. As discussed below, energy densities at least ten times higher than this scale can be achieved in head-on collisions of heavy nuclei at energies of 100 GeV per nucleon in the center of mass frame, and almost certainly were realized in the early Universe. At temperatures in excess of T_c nuclear matter is predicted to consist of unconfined, nearly mass-

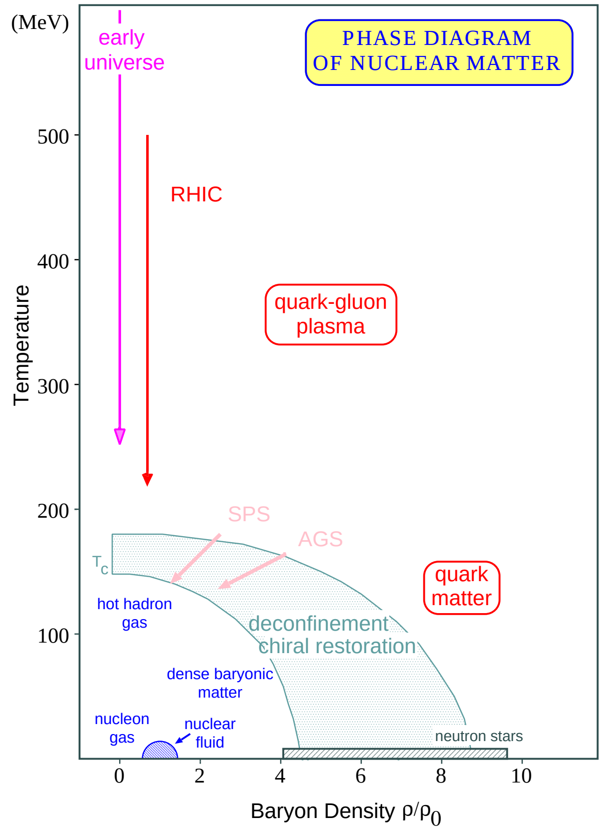

Figure III.1: Phase diagram of nuclear matter.

less quarks and gluons, a state called the *quark-gluon plasma*.

The study of deconfinement and chiral symmetry restoration is the primary motivation for the construction of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Whereas the high energy electron-nuclear interactions that will be studied at CEBAF probe the quark substructure of individual nucleons, its role in the nuclear force and, eventually, its significance in nuclear structure, RHIC will explore how the properties of matter are controlled by the structure of the physical vacuum on distance scales large compared to the size of a single nucleon. The goals of these two new facilities for nuclear physics research are thus complementary. The complete understanding of nuclei and strongly interacting matter in terms of the Standard Model requires the vigorous pursuit of both directions.

Astrophysical relevance

Modern cosmology asserts that during the first few millionths of a second after the Big Bang, when the temperature exceeded 150 MeV, the entire universe was filled with a quark-gluon plasma. After the universe cooled to temperatures below T_c, the primordial plasma transformed into a gas of nucleons and mesons and eventually into the nuclei and leptons we now observe as relics of the cosmic Big Bang. Should the cosmological quark-hadron transition involve significant density inhomogeneities as they are known to develop during first-order phase transitions, light element nucleosynthesis may lead to an observable excess in the primordial abundance of the elements Be or B. Such density variations may even lead to strange quark matter nuggets and planetary-mass black holes that could account for some of the unobserved ("dark") matter in our universe.

Under the pull of gravity, the energy density in the cores of neutron stars is thought to approach or exceed the critical value of 1 GeV/fm^3, rendering their structure sensitive to the equation of state of very dense matter. Experiments with relativistic heavy ions at current facilities, as described below, are now providing first empirical information on the equation of state of high baryon density matter relevant to neutron star structure.

In addition to the deconfinement transition, Figure III.1 illustrates another phase transition in nuclear matter at much lower excitation energies analogous to the gas-liquid transition in condensed matter physics. This transition is predicted to occur at temperatures around 15 MeV and hence is of particular interest to the physics of supernova explosions, where such temperatures are generated. Intermediate energy heavy ion collisions at energies around 100 MeV per nucleon are currently the most promising tool to search for the liquid-gas transition in the laboratory.

Characteristics of heavy ion physics

To explore the phase diagram of nuclear matter, it is essential to determine the degree of thermalization, i.e. of equipartitioning of the available energy over all accessible degrees of freedom, achieved during the reaction. Knowledge of the thermodynamic properties of the short-lived excited state requires the detection of a large number of particles in the final state and the measurement of their yields and momentum spectra.

To satisfy these requirements, state-of-the-art detectors for heavy ion reactions have the capability of particle identification over a very large acceptance range and are able to handle extreme particle multiplicities. Because the thermodynamic conditions achieved in individual collisions vary due to fluctuations and differences in impact parameter, the complete analysis of final states event by event is highly desirable. Rapid progress in detector development, combined with improvements in electronic data processing, has rendered many experiments in this field possible which were inconceivable only a few years ago. By constantly expanding the limits of detector design, heavy ion physics contributes significantly to technological progress.

Heavy ion collisions are the experimental means to produce new phases of nuclear matter, but understanding the underlying collision dynamics requires a reliable transport theory to relate the observables back to the fundamental dynamics. There has been substantial progress in the last five years in the development of transport theory and application to heavy ion collisions in various energy regimes. At low energies, one-body transport with mean field and two-particle collisions has proven useful. At higher energies, the transport models necessarily include the quark and gluon degrees of freedom within the colliding nuclei.

At present, transport models successfully describe many experimental observables, such as particle yields, momentum spectra, and identical particle correlations, over a range of more than three orders of magnitude in beam energy per nucleon. They have recently been extended to higher energies for the future heavy ion colliders to provide a description of the known physical processes. Comparison to these models allows a search for evidence of collective effects. However, large fluctuations in the distributions of the emitted particles, which are a special feature of phase transitions, call for further developments in transport theory. New approaches are being developed, but will require substantial theoretical work to be brought to fruition.

The following sections address, in turn, the physics issues associated with three most important regions of the nuclear phase diagram (Figure III.1): Nucleonic matter and the liquid-gas phase transition, the regime of dense baryonic matter and its transition to quark matter, and finally the quark-gluon plasma.

The Regime of Nucleonic Matter

Nuclei can be viewed as droplets of a Fermi liquid composed of neutrons and protons. Theoretically, it is predicted that infinite nuclear matter undergoes a transition from liquid to gaseous phase at subnuclear density ($\rho < \rho_0$) and can support a mixed phase equilibrium at temperatures up to a critical temperature of $T_c \approx 17$ MeV. As is the case for macroscopic liquids, this phase transition is accompanied by a singularity in the specific heat for densities and temperatures in the mixed phase region. For subnuclear densities $\rho \approx 0.3\rho_0$, density fluctuations and the abundances of light droplets (fragments with nucleon number $A = 3-50$) are predicted to increase with temperature to a maximum at the critical temperature and decline thereafter. Calculations predict that these signatures for the nuclear liquid-gas phase transition should persist, albeit in modified form, in the decay of the finite charged nuclear systems that can be produced via nuclear collisions, e. g. at the heavy ion accelerators at Michigan State University and Texas A&M University. Full characterization of this bulk phase transition is one of the major objectives of intermediate energy heavy ion research.

A second objective concerns the equation of state of nuclear matter at higher than normal densities, achieved in nearly head-on collisions of nuclei at incident energies $E/A > 100$ MeV. In such collisions, a high pressure develops within the high density "participant" region formed by the overlap of projectile and target nuclei. This pressure is related to the nuclear equation of state and to collision rates within the nuclear medium that are governed by cross sections which may be strongly modified from their values in free space. Experiments providing information about the pressure and the nucleon cross-section in medium are among the highlights of recent achievements in this area.

Figure III.2 presents experimental evidence for a liquid-gas phase transition in central collisions between heavy nuclei. The solid points show the rise and fall of the fragment multiplicities as a function of incident energy for central Kr+Au collisions. At incident energies between 50 and 100 MeV per nucleon large nuclear fragments are produced abundantly, as expected for a mixture of liquid and gas phases. At higher incident energies the larger fragments give way to smaller ones, indicating the onset of vaporization. First generation transport models do not faithfully reproduce the observed trends with incident energy, motivating the development of a better description within quantum transport theory of the fluctuations that give rise to fragment formation.

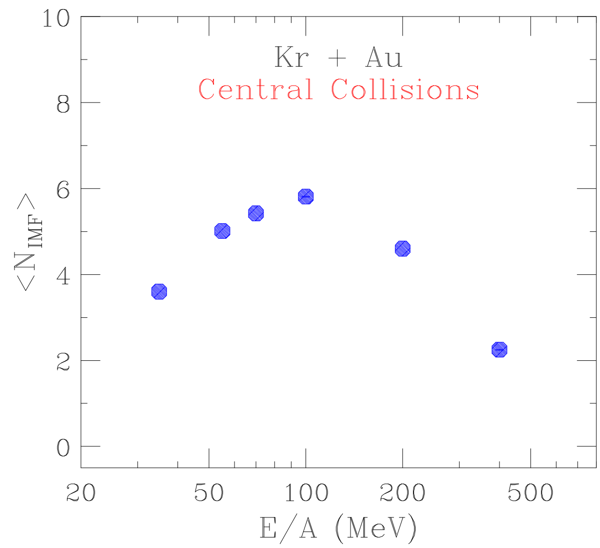

Figure III.2: The solid points show the rise and fall of the fragment multiplicities as a function of incident energy for central Kr+Au collisions. This behavior is consistent with a liquid-gas phase transition around 100 MeV/nucleon.

This signature of the liquid-gas transition is not unambiguous, because light nuclear fragments with $A = 6 - 50$ could also be evaporated over somewhat longer time scales (of order 10^{-20} s) from the surfaces of larger nuclei. It is important, therefore, that the time scales found experimentally by analyzing the Coulomb final state interactions between fragments are less than 3×10^{-22} s, consistent with a bulk disintegration and much less than the time required for the system to decay sequentially, equilibrating between each successive step.

The liquid-gas phase transition is associated with expansion and fragmentation of the nuclear system from a dilute phase. Evidence for this expansion has been obtained from fragment energy spectra and comparisons to statistical models. The impact parameter and incident energy dependences of fragment charge distributions have recently been measured. Event-by-event analyses of the moments of fragment charge distri-

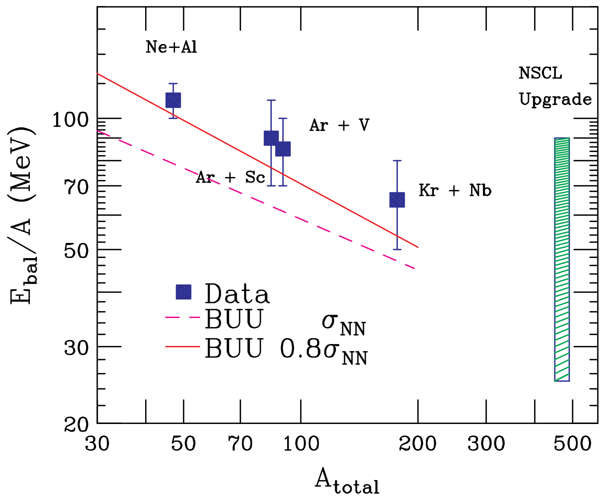

Figure III.3: The solid squares indicate the mass dependence of the balance energy. The dashed and solid lines indicate the transport model calculations which assume free nucleon-nucleon cross sections and nucleon-nucleon cross sections reduced by 20%, respectively.

butions begin to allow extraction of the critical exponents for the liquid-gas phase transition.

Significant progress has also been made towards determining the nuclear equation of state at high density. This experimental program relies upon measurements of the collective velocity field or "flow" within the expanding nuclear system at breakup. The relationship between this velocity field and the pressure within the high density "participant" region has been analyzed in the framework of nuclear transport theory. Observed phenomena include a sideways directed flow in the reaction plane perpendicular to the total angular momentum and a significant outward expansion of the participant region.

At incident energies around 400 MeV per nucleon, comparisons of symmetric and asymmetric colliding systems have set separate constraints upon the momentum and configuration-space dependences of the nuclear mean field. The incident energy where transverse flow first appears, called the "balance energy", plays a special role because it provides quantitative information about the medium modifications of the nucleon-nucleon cross section. Figure III.3 shows the measured value of the balance energy as a function of the combined nuclear mass. The comparison with transport models reveals that in the nuclear medium the nucleon-nucleon cross section is only slightly reduced from its free value.

Future scientific opportunities

A quantitative description of the liquid-gas phase transition from nuclear collisions requires knowledge of the time evolution of the temperatures and densities of these systems. Such reaction trajectories may not follow equilibrium paths. For example, transport model calculations have indicated that one may expect unusual toroidal, cylindrical or bubble-like breakup geometries for specific reactions. The prediction of cylindrical breakup geometries has already been confirmed by experiment. Techniques to extract information about temperature, density, and the geometry of the system have been developed recently. The experiments require large beam intensities at energies around 100 MeV per nucleon for light and heavy nuclei as will become available with the proposed upgrade of the NSCL facility at Michigan State University.

In order to extrapolate experimental observations to the conditions of neutron star matter, the size of the system must be varied over a range of values up to the largest accessible, containing nearly 500 nucleons. Likewise, the fragment yields must be studied as a function of the proton-to-neutron ratio of the combined system of both nuclei to separate the effects of size and the Coulomb force. This requires capabilities for investigating reactions induced by beams with exotic charge-to-mass ratios.

The isospin dependence of the nuclear equation of state is an issue of fundamental importance to the theory of supernovae and the formation and ultimate stability of neutron stars. Directed transverse flow measurements using the radioactive nuclear beams of the proposed MSU upgrade provide information on the nuclear equation of state for significant variations in the proton-to-neutron ratio. Complementary information about nuclear compressibilities will become accessible by the scattering to the giant monopole resonance of unstable nuclei.

Hot and Extremely Dense Hadronic Matter

Exploring the high density region of the phase diagram at low or moderately high temperature (the right side of Figure III.1) is of special interest as it provides access to deconfined quarks in a regime where chiral symmetry is restored, but gluons are not of major importance (hence the term quark matter and not quark-gluon plasma).

Systems with the maximum baryon density are prepared by colliding atomic nuclei at an energy where they just barely stop each other. Recent experiments have shown that the optimal energy is in the range of $2 - 5$ GeV per nucleon in the center-of-mass frame. This makes the Brookhaven AGS, with a c.m. collision energy of about 2.5 GeV per nucleon, the ideal tool for studying extremely dense matter. The CERN SPS, reaching $5 - 10$ GeV per nucleon, provides somewhat lower baryon density but higher energy density, making new observables accessible.

Experimental heavy ion programs have been in progress at both laboratories since 1986, initially with oxygen beams and then mostly with silicon and sulphur beams. A number of major experiments have provided a wide variety of data which include several surprises. These programs routinely involve careful comparisons to p+p and p+A collisions in the search for evidence of new physics. The recent advent of gold beams at the AGS in 1992 and lead beams at the SPS in 1994 are long awaited milestones in the field. The heaviest systems should equilibrate faster and at a higher density and temperature, enhancing the signals of quark matter over the hadronic background. A broad array of detectors is in place, capable of dealing with unprecedented multiplicities. (There are 800 final-state hadrons per event at the AGS and about twice that at the SPS.)

Experimental data on nucleon distributions and transverse energy production give a consistent picture of the degree to which nuclei stop each other in the center-of-mass frame. The stopped kinetic energy is transformed into other degrees of freedom, such as thermal energy, particle production, and transverse collective expansion. Data at the AGS for the heaviest nuclei are consistent with the maximum amount of energy deposition or “full stopping”. For S+S collisions at the SPS only two thirds of the available energy is stopped.

Figure III.4 shows how nucleons increasingly accumulate at central rapidity for more central collisions and heavier systems at the AGS. The inelastic nucleon-nucleon cross section has been measured not only for the first but also for successive collisions and is found to be the same as its free value. This is essential input into calculations of the maximum baryon and energy density that are based on one-body transport theory.

Such calculations reproduce the amount of stopping observed experimentally and give maximum baryon densities at the AGS of $5 - 10$ times

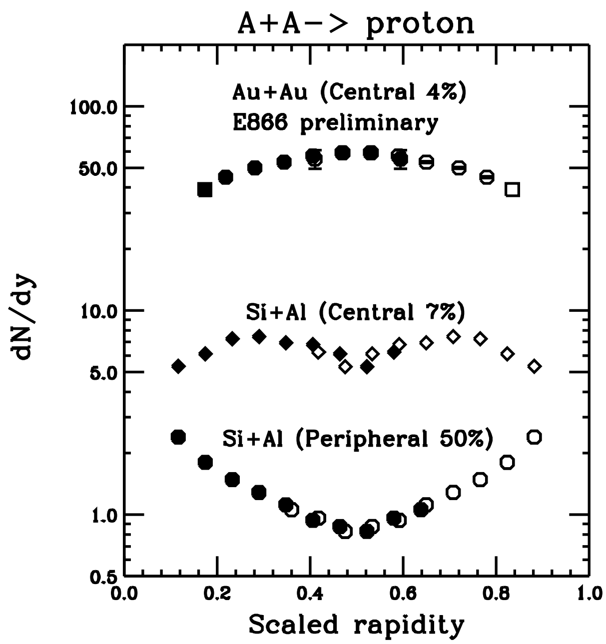

Figure III.4: Rapidity distributions for protons from Si+Al and Au+Au collisions obtained by the E802 collaboration. The rapidity is normalized to the beam rapidity. The change of shape indicates increased stopping for Au+Au.

normal nuclear density ρ_0 and $(3 - 6)\rho_0$ at the SPS. The values increase about a factor of two going from the lightest (Si+Si or S+S) to the heaviest (Au+Au or Pb+Pb) symmetric systems. The initial temperatures are still uncertain because they are difficult to measure directly.

Final-state hadrons decouple (“freeze out”) when their mean free path exceeds the size of the system. Experiments at both accelerators have produced a rather complete picture of the emitted hadrons for the lighter Si and S projectiles. At the AGS these observed hadrons include p, n, Δ^{++}, $\bar{\text{p}}$, $\bar{\text{d}}$, Λ, $\bar{\Lambda}$, Ξ^-, $\pi^{\pm}$, $\text{K}^{\pm}$, K^0_S, and ϕ; at the SPS the Ξ^+, Ω^-, Ω^+, π^0, ρ/ω, J/ψ, and ψ' have been observed, in addition. With this wealth of data one can now investigate whether the final hadronic state is in equilibrium. A system in local thermal and chemical equilibrium is described by two parameters, the temperature T and baryon chemical potential μ.

For the AGS, comparison to data reveals remarkable agreement for a freeze-out temperature of $120 - 140$ MeV and a baryon density of 30–40% of normal nuclear matter density for abundances from pions to antideuterons. The freeze-out parameters deduced from the observed hadron abundances at the AGS are indicated in the phase diagram of Figure III.5. An analysis

Probing the Vacuum

The Greek scientist-philosophers invented the concept of space with nothing in it over 2,500 years ago. The notion has continued to intrigue scientists — and science fiction writers — right up to the present day. But modern physicists no longer think of the vacuum as empty. Instead, they see it as having a complex structure which determines the laws of nature. And increasingly, physicists are exploiting that hidden structure in remarkable ways: by creating in the laboratory conditions thought to exist in the earliest microseconds of the universe; and by examining types of matter that no longer exist in our world.

According to nuclear quantum theory, the vacuum has both energy and mass. It has been described as a “sea” of quark-antiquark pairs — quarks being the invisible constituents from which all matter is made. But matter is present in the vacuum only instantaneously, as manifestations of fluctuating fields of nuclear and electromagnetic forces that have an average value of zero. Normally, in fact, these fluctuations are too small to be observed — but not always.

To explore the vacuum, nuclear physicists plan to heat it up for brief instants to unimaginable temperatures — 1500 billion degrees. To do this, they will use the Relativistic Heavy Ion Collider, a new accelerator being built at Brookhaven National Laboratory. When the nuclei of two heavy atoms propelled by the accelerator collide with sufficient force, they pass right through each other, converting some of their energy to heat. The tiny piece of vacuum between the two retreating nuclei gets very hot. Under these conditions, theory predicts, the structure of the vacuum will “melt” — creating disordered conditions comparable to those in the first millionth of a second after the Big Bang.

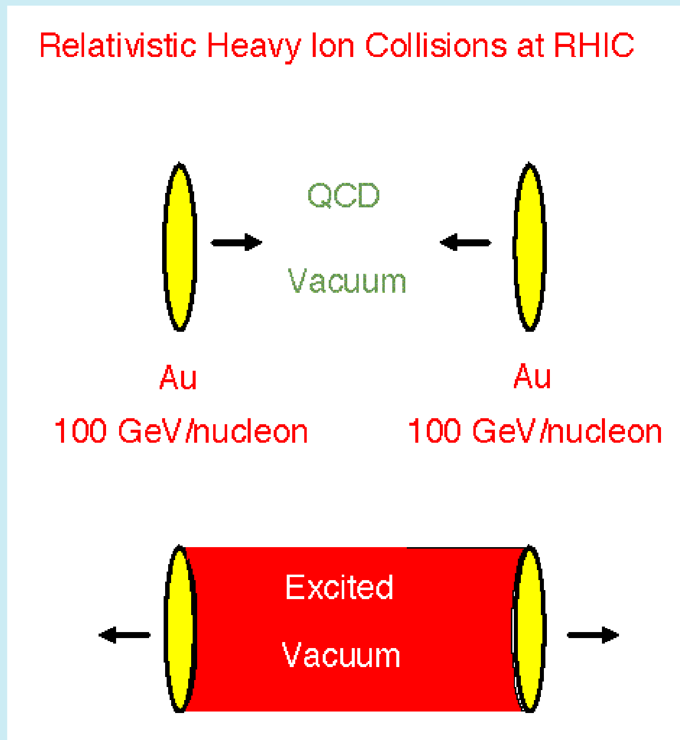

Figure III.A The temperature of the excited vacuum is expected to reach more than 1 trillion degrees in relativistic heavy-ion collisions, releasing quarks and gluons into a plasma state. Such conditions existed only in the first few millionths of a second after the Big Bang.

Figure III.B Aerial view of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. The beam from the Tandem van de Graaff travels to the Booster and Alternating Gradient Synchrotron (AGS) where it is accelerated further before being injected into the two counter-rotating rings at RHIC. In RHIC the beams are accelerated to very high energies (20 trillion electron volts in each beam for a gold nucleus) and then collided with one another. The RHIC accelerator and experiments are due to start operation in 1999.

In that early phase of the universe, physicists believe, quarks were not confined within protons and other particles as they are now, but moved freely about in what physicists call a "quark-gluon plasma." Because the relationships between quarks were not fixed, neither were the physical constants that characterize our universe and the types of matter that exist in it — many different universes could in theory have emerged. As the plasma began to cool, however, protons and other particles began to condense out, eventually forming atoms, then stars and galaxies. That "phase change" from a quark-gluon plasma to normal forms of matter essentially froze in place a particular set of relationships among quarks — in effect, selecting a particular structure for the vacuum and hence fixing the physical relationships that govern our world. By colliding heavy nuclei, physicists hope to briefly reverse the phase change, again freeing quarks in a quark-gluon plasma and giving physicists a unique opportunity to explore its properties — and creating an experimental window into the early universe.

At least two types of signals will tell scientists that they have succeeded in melting the vacuum. As the plasma cools, some of it may condense into matter that doesn't belong in our world — matter that, in effect, incorporates characteristics from a different possible universe. As such matter adjusts to this universe, it is expected to emit particles with unusual properties that physicists can detect. Physicists can also observe the duration of nuclear reactions, which are expected to take longer under conditions found in a quark-gluon plasma.

These new experiments thus offer physicists not only the opportunity to probe the vacuum but, for the first time in human experience, to alter its properties and to explore the conditions of the early universe. Never has empty space seemed so full of possibilities.

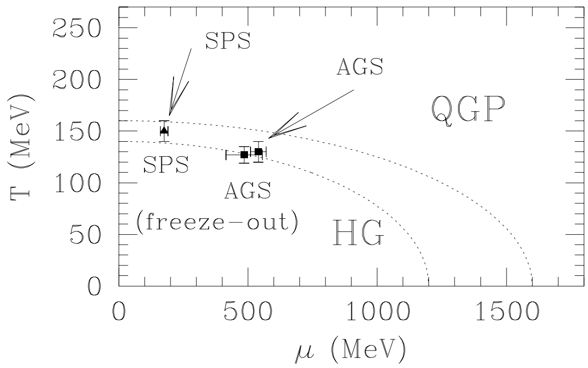

Figure III.5: Thermal freeze-out parameters shown in the phase diagram of nuclear matter. The two dashed lines indicate the location of the expected phase boundary and its degree of uncertainty. The solid points with error bars show the freeze-out values deduced from AGS and SPS data with flow; the arrows indicate how the freeze-out conditions may be approached during the expansion of the fireball. The horizontal axis shows the baryon chemical potential μ, which is a measure of the baryon density.

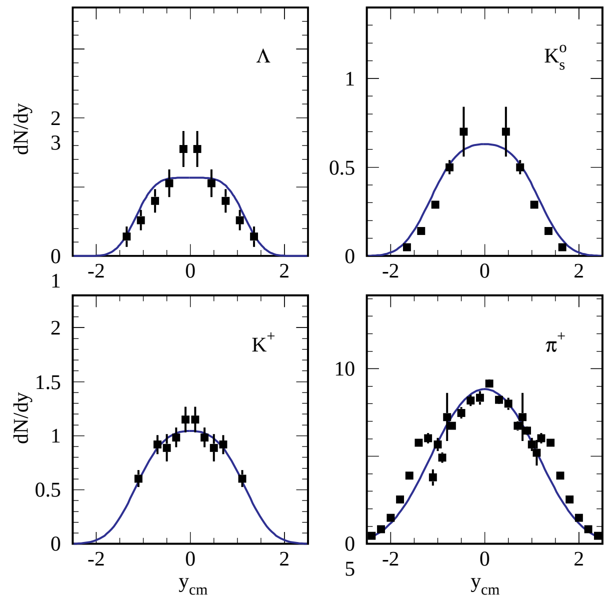

Figure III.6: Rapidity distributions of different hadrons for central 14.6 GeV/c per nucleon Si+Al collisions at the AGS (data from experiments E802, E810 and E814) in comparison with thermal distributions for a source at temperature $T = 120$ MeV expanding with average velocity $\langle\beta_l\rangle = 0.52$ along the beam direction (solid lines).

of the CERN data gives a freeze-out point also shown in the figure.

The freeze-out volume can be independently determined by measuring the correlation functions of two identical particles (see also the sidebar "Probing the Vacuum: Part II"). These have been measured for protons, pions and kaons at both accelerators. The data quantitatively confirm the freeze-out picture given above and show that the system has expanded considerably before the hadrons decouple. Hadronic cascade models based on free cross sections reproduce the observed correlation functions and show that the system has expanded from very high initial densities to a dilute state at freeze-out.

The rapidity distributions of various hadrons at freeze-out also indicate expansion of the system. Figure III.6 shows distributions measured at the AGS, which can be described as thermal emission from a longitudinally expanding system. Furthermore, transverse momentum spectra indicate transverse flow; the spectra are flatter for more massive particles and generally differ from simple Boltzmann distributions. Measurement of both the two-particle correlation functions and the hadron singles spectra allow determination of the expansion velocity and the freeze-out temperature without relying on models of the collisions.

Recently, for semi-central Au+Au collisions anisotropic flow has been observed. This feature was first discovered in medium energy heavy ion collisions at the Bevalac and was used to constrain the nuclear equation of state. As an ever more complete experimental picture emerges, progress will be made exploring the equations of state of highly excited hadronic and quark matter. The equation of state of quark matter is predicted to be significantly softer than that of hadronic matter at the same density, and hydrodynamic calculations for hadronic and quark matter predict observable differences.

The strong suppression of strange hadrons observed in p+p collisions was predicted to be absent in heavy ion collisions if a quark-gluon-plasma is formed. Indeed, heavy ion experiments at the AGS and SPS have found an enhancement by a factor of two of strange hadrons compared with p+p yields. Some of the features of strangeness production, in particular the kaon and lambda yields, can be accounted for by hadronic cascade models via secondary collisions. However, in order to explain the Ξ^- yield at the AGS and that of strange antibaryons at the SPS, hadronic cascade models must invoke new physics, such as statistical decay of small quark matter clusters formed during the reaction.

A definite prediction for a deconfined state is that the color interaction between quarks is screened. Therefore, bound states like the J/ψ

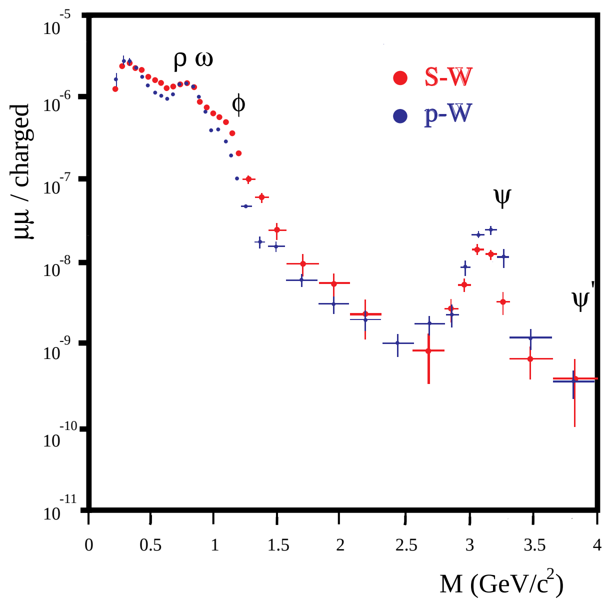

Figure III.7: Inclusive $\mu^+\mu^-$ invariant mass spectra in 200 GeV/c per nucleon S+Au collisions (data from experiment NA34). The S+Au data (red points) are compared with measurements in p+Au collisions (blue points), which are scaled by a factor 32. The comparison reveals an excess in the region between twice the pion mass and the J/ψ mass, which is dominated by semileptonic decays of charmed mesons.

cannot form or are easily dissolved. Even larger bound states like the ψ' are dissolved first, and show stronger suppression. Experiments at the SPS report suppression of the J/ψ with increasing centrality of the collisions as compared to p+p collisions. However, J/ψ suppression has been observed in p+A collisions as well, which can be used to determine the initial state scattering effects and final state J/ψ reinteractions with co-moving hadrons. Recent data from CERN for the ψ' yield as a function of centrality show for the first time a decrease in the ratio ψ' to J/ψ, unlike the case for p+A collisions.

Radiation of real or virtual photons reflects the thermal history of the radiating system. A phase transition with a finite latent heat will produce a system at a lower initial temperature and will possibly introduce a long delay during re-hadronization, resulting in radiation from a relatively cool, but long-lived source. Other modifications of the photon spectrum could come from in-medium modifications of hadrons as the restoration of chiral symmetry is approached. Three different di-lepton experiments at the SPS have reported excess production in the mass range between twice the pion mass and the J/ψ, shown in Figure III.7. The source of this excess will be investigated experimentally and theoretically in the next few years.

Future scientific opportunities

Using the newly available Au and Pb beams at the AGS and SPS, the properties of nuclear matter at high baryon density and the dynamics of the reaction process will be studied in the next few years. The focus of these investigations will be on potential signals of new physics, such as a long-lived mixed phase. The experiments will determine the particle and energy densities, degree of equilibration, baryon chemical potential, temperature, flow, flavor saturation, and the time evolution of the collision system. This information is vital to understanding the transient high density matter formed in these collisions. The dependence of collective flow phenomena on incident energy, atomic number, and the type of emitted particle will be mapped out at the AGS, with the goal of distinguishing between stiff baryonic matter and soft quark matter.

The heavy beams will permit a systematic study of the multiplicity dependence of the presently unexplained excess of low and intermediate mass dilepton pairs observed in light ion collisions, in order to establish the production mechanism. This type of experiment is presently missing in the AGS program and would be a very valuable addition. A search for direct photons is being made in collisions of heavy nuclei at the SPS. If an excess of direct photons exists in collisions at these energies, they should become more prevalent for the heavier systems. The systematic study of the suppression of J/ψ and ψ' as a function of transverse energy for Pb+Pb reactions at the SPS is important to differentiate rescattering mechanisms from possible suppression in a quark-gluon plasma.

The effects of the high density medium on the mass and width of the ϕ-meson will also be studied. Modifications of the properties of hadrons in the medium are predicted when chiral symmetry is restored at high densities. A possible enhancement of kaon spectra at very low transverse momenta, indicating in-medium modifications of the kaon at high density, will be studied in Au+Au collisions at the AGS.

The high baryon density achieved at the AGS, in combination with the enhanced strangeness production, make this facility an ideal place to search for new, multiply strange states of nuclear matter. The new, more sensitive searches

Probing the Vacuum: Part II

To study conditions that occurred in the first few millionths of a second of the universe, nuclear scientists are resorting to some unusual approaches. First they have to “melt” the vacuum, creating temperatures as high as 1500 billion degrees by colliding the nuclei of two atoms at very high speeds. Then they have to study a region of space not too much larger than the nucleus of an atom and which exists only fleetingly. Finally, they have to measure accurately the size, shape, and lifetime of this volume of melted vacuum.

As it happens, nearly 40 years ago astronomers studying the size of distant stars developed a technique that makes it possible to do just this. The technique is based on the phenomenon that photons from opposite sides of a star can interfere with each other on their way to earth — a consequence of the fundamental law of quantum mechanics. The interference phenomena can be detected, and the range of observing angles over which it occurs is related to the size of the emitting star.

Nuclear physicists have adapted this interference technique to study the tiny region of altered space created by nuclear collisions. So small is the emitting region, however, that it would appear to human observers as would a star, not in our galaxy, but at the edge of the universe. And instead of photons, it is the interference of protons or unstable particles such as mesons given off by the superheated vacuum that is detected. Indeed, physicists have greatly extended the technique by measuring not just the direction of the observed particles, but also their energies. This allows them to determine not just the size, but the shape and lifetime of the source as well.

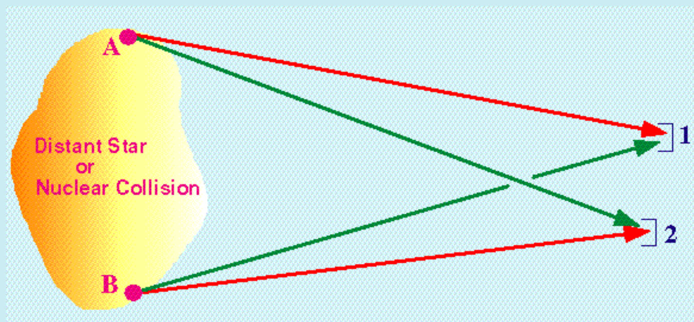

Figure III.C Representation of the Hanbury-Brown and Twiss effect. Photons (or other identical particles) emitted from a star (or a nuclear collision) and recorded in detectors 1 and 2 show an increased coincidence rate if they are nearby in energy and time. The increased rate can be used to measure the separation between points A and B.

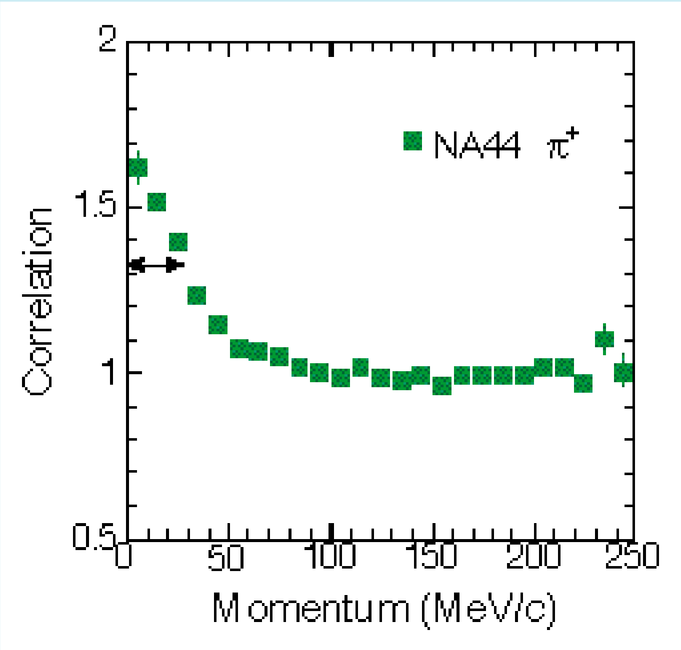

Figure III.D The rate of detecting positively charged pi-mesons (π^+) which are emitted from a high energy collision between two heavy nuclei as a function of their relative momentum. In this example, from CERN, the width of the increase toward small relative momentum (see arrow) indicates that the diameter of the emitting source is about one trillionth of a centimeter.

The interference technique will be a method of choice for studying the collisions at the Relativistic Heavy Ion Collider now being built at Brookhaven National Laboratory. In fact the facility will be able to detect, track, and analyze thousands of particles at the same time, using high speed detectors and computers — a remarkable technical achievement. For experiments designed to probe the substructure of the vacuum, very high energies are needed, energies where even very heavy ions can't be stopped in a collision and so will pass through each other. Large volumes are also needed so the collisions will be of gold nuclei. And it is in probing the residue of such a collision that nuclear physicists hope to detect a vacuum that has undergone a phase change — "melted" to create, for the first time in a laboratory, conditions like those that prevailed during the first millionth of a second of the universe — a plasma of quarks, antiquarks and gluons.

The collision region is expected to expand rapidly, like a miniature fireball, moving at velocities about one third the speed of light and in the process cooling quickly. In this cooling process the quarks, antiquarks and gluons coalesce to produce the particles that generate the interference pattern. The interference technique will capture an image of the altered collision region — which according to preliminary experiments is likely to be up to two or three times the diameter of the gold nuclei. But just what other insights or unexpected results will arise from probing the vacuum will have to await the completion of the new accelerator and its state-of-the-art detection tools.

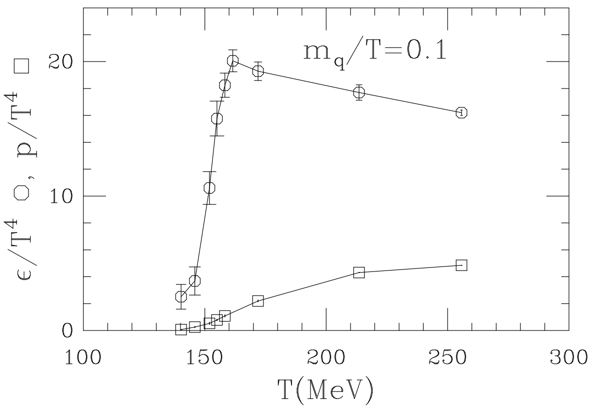

Figure III.8: Energy density ϵ (upper curve) and pressure p (lower curve) from a numerical evaluation of QCD "on the lattice" with two light flavors of quarks. ϵ and p are divided by T^4 to exhibit the sudden rise in the number of thermally excited degrees of freedom at the critical temperature $T_c \approx 150$ MeV due to liberation of color and chiral symmetry restoration.

at the AGS and SPS for the H-particle (a neutral, doubly-strange dibaryon) and strangelets will either lead to their discovery or place stringent new limits on their production cross sections. The observation of "conventional" multi-strange hypernuclei would permit limits to be set on the possible existence and metastability of small strangelets.

With sufficient beam time, significant progress can be made in the next few years. Based on the experience of rapid progress during the last five years, the expectation is that indications of new physics from the lighter beams will be confirmed and further explored with the heavier beams.

Quark-Gluon Plasma and RHIC

Exploring the phase diagram of nuclear matter at vanishing net baryon density (the upper left part of Figure III.1) is of special interest, because this kind of matter filled the very early universe, and quantitative theoretical predictions are possible in this regime with currently available techniques. The design energy of RHIC was chosen such that the heaviest nuclei are predicted to become transparent to the nucleons in the other colliding nucleus. Thus, the hot and dense quark-gluon plasma (QGP) created in the central rapidity region is matter-antimatter symmetric, i.e. has nearly vanishing net baryon density.

Numerical solutions of QCD "on the lattice" provide guidance to our exploration of the deconfinement phase transition under these conditions. There is now solid evidence that the transition temperature with two flavors (up, down) of light quarks is $T_c \approx 150$ MeV (see Figure III.8). The precise order of the phase transition for the physical case of up, down and strange quarks is still unclear, but a strong change in the number of active degrees of freedom in a narrow temperature range around T_c of order ± 10 MeV is firmly established.

The perturbative description of the equation of state and of the transport properties of the quark-gluon plasma has made rapid progress in recent years. Theorists have learned how to systematically include screening effects into the description of single-particle and collective modes of the quark-gluon plasma. This has facilitated quantitative predictions for some of the most interesting QGP signatures, such as photon and dilepton spectra, and for the transport properties of the quark-gluon plasma. The results indicate the possibility of very rapid thermalization (less than 3×10^{-24} s) in nuclear collisions at RHIC due to chaotic plasma dynamics.

The techniques of perturbative QCD, which were developed in the context of QCD jet formation in e^+e^- and $p\bar{p}$ annihilations, have been applied to describe the earliest phase of nuclear collisions at RHIC in terms of a cascade of quarks and gluons. These calculations have led to the expectations of a very high initial temperature ($T = 350 - 500$ MeV) at RHIC and copious gluon production. Quantitative predictions for the full space-time evolution of dense QCD matter at RHIC energies up to the final hadron distributions are now available. Figure III.9 shows results of a calculation that reproduces charged particle multiplicities for Au+Au collisions at AGS and SPS and its predictions for RHIC.

QGP signatures

Specific signatures that can be used to probe the phase transition between hot hadronic matter and a quark-gluon plasma, and to study the characteristic properties of the quark-gluon plasma have been identified:

- The investigation of average transverse momenta and spectral slopes as functions of particle multiplicity will permit the determination of the bulk thermodynamic properties of the dense matter created in the nuclear collision. A large latent heat associated with the phase transition is predicted to re-

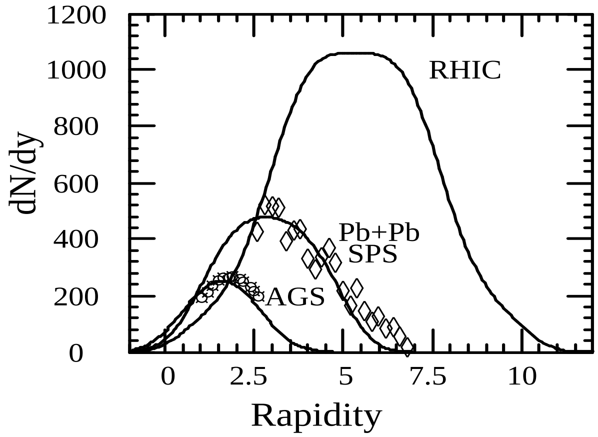

Figure III.9: Evolution of the charged particle multiplicity for central Au+Au (Pb+Pb) collisions from AGS and SPS to RHIC energies. The diamonds show data from experiments E-877 (AGS) and EMU-01 (SPS); the lines correspond to calculations using the partonic cascade model HIJING. The rise is almost entirely due to increased meson production.

veal itself in a characteristic S-shaped curve for these two variables.

- Heavy vector mesons, especially the charmonium states J/ψ and ψ', are excellent probes of color deconfinement. It is predicted that J/ψ production is suppressed strongly if a QGP is formed. The suppression will be stronger for ψ', but the Υ should remain unsuppressed.

- The proximity of chiral symmetry restoration is probed by possible changes in mass and width of the light vector mesons, which may be detected via their lepton-pair decays. Unusual event-by-event fluctuations in the ratio of pion charge states are also a characteristic feature of a second-order chiral phase transition.

- Enhanced yields of multistrange baryons and antibaryons signal the rapid approach to flavor equilibrium that is expected from the high gluon content of the QGP.

- Direct photons and lepton pairs probe the interior of the QGP. Their spectra and yields track the thermal history of the dense matter and provide information about the temperature and duration of the mixed phase. Enhanced charm production would indicate a very hot and dense gluonic phase right after thermalization. A long-lived mixed phase would also manifest itself in an increase in the source lifetime derived from two-particle correlations.

- Quark jets probe the QGP through increased energy loss of the leading fragment hadrons and changes in the jet-jet angular correlation.

In preparation for the experimental program at RHIC, the various proposed signatures of a quark-gluon plasma have been under intense theoretical scrutiny. The energy loss of jets in a quark-gluon plasma has been calculated and quantitative predictions for jets propagating through dense matter are now available. The dissolution of the J/ψ and other heavy vector mesons in the deconfined phase has been carefully studied, and a comprehensive description of J/ψ and ψ' suppression by their hadronic environment has been developed. A new signature for the chiral phase transition, the formation of disoriented chiral condensates, was proposed. Such a state would have highly specific experimental characteristics, such as unusual pion charge ratios, or charge correlations, such as were seen in some cosmic ray events. Significant progress has also been made in our understanding of suitable signatures for a long-lived mixed phase, such as lepton pairs, vector mesons, and identical particle correlations.

Fundamental challenges in this field are to develop a quantitative description of the phase transition from hadronic to quark-gluon matter, to determine the structure of nuclear matter on both sides of the transition, and to identify reliable experimental signatures for chiral symmetry restoration and deconfinement. An important step toward that goal is the refinement of quantum transport theory for nonequilibrium processes to a point where it can serve as a reliable tool for the description of the reaction dynamics from the initial stage of a heavy ion collision up to the final disassembly phase. There is also a need for definitive Monte Carlo calculations of QCD to determine the precise characteristics of the phase transition in the presence of physical up, down, and strange quarks. The formulation of an effective dynamical theory of hadronization would further strengthen the reliability of predictions for some of the proposed quark-gluon plasma signatures.

Experimental perspectives

The construction of RHIC, which was begun in 1991 and is scheduled for completion in 1999, proceeds on target. Since the 1989 Long Range Plan, a complement of collider detectors has been designed. Two major detector systems, PHENIX and STAR, as well as two smaller detectors, BRAHMS and PHOBOS, have been approved in their baseline configurations and are presently under construction. PHENIX will specialize in the measurement of leptons and photons, together with some hadron detection at mid-rapidity. STAR will detect all charged particles over a large rapidity interval for event-by-event analysis. Both detectors have extensive calorimetric capabilities. BRAHMS will measure identified particle spectra over the full rapidity range with small acceptance, and PHOBOS will provide high-resolution charged particle tracking with emphasis on detection of low momentum particles at mid-rapidity.

The complementary capabilities of these detectors will permit the inception of a vigorous scientific program at RHIC immediately after turn-on. Initial runs at RHIC will provide:

- First results on the energy densities, multiplicity densities, baryon stopping, degree of equilibration, baryon chemical potential, temperature, flow, and strangeness saturation to determine the degree of equilibration at the parton level in Au+Au collisions.
- First "pictures" of the spacetime evolution of matter at unprecedented energy density from $\pi\pi$ and KK correlations at RHIC, which can provide evidence for the presence of a long-lived mixed phase.
- First tests of the effects of the dense medium, via chiral symmetry restoration, on the mass, width, and decay modes of the ϕ-meson.
- Measurements of event-by-event fluctuations in the ratio of pion charge states, especially at low transverse momenta, to investigate a possible second-order chiral phase transition.
- Measurements of the suppression of J/ψ as a function of transverse energy for Au+Au collisions at RHIC, where the initial energy density is expected to be a factor of ten higher than that achieved in reactions at the present fixed-target facilities.
- Measurements of particles at high transverse momentum to test the dynamics of hard partons in the quark-gluon plasma.

In addition to collisions between heavy nuclei, an extensive program of p+p and p+A collisions at RHIC is anticipated from the start. The primary goal of this program will be to obtain precise background measurements of the various proposed QGP signatures in p+p and p+A interactions. This has been found to be an essential component of the experimental programs at the lower energies, especially for the strangeness and J/ψ signals. An important aspect of proton-induced reactions at RHIC is that they will provide crucial information on the nuclear parton structure functions. It is a special design feature of RHIC that p+p, p+A, and A+A collisions can be studied at the same c.m. energy, so that detector efficiencies and systematic errors largely cancel.

The proposed additional experimental equipment for the two major RHIC detectors will extend their capabilities and facilitate a full program of searches for specific QGP signals (including J/ψ and ψ' production, strangeness saturation, open charm production, electromagnetic radiation, parton propagation in the plasma, critical fluctuations, and thermodynamic properties). This equipment should be available as soon as possible to exploit the full scientific discovery potential of RHIC.

The recent approval of the Large Hadron Collider (LHC) project at CERN has opened the possibility to pursue the study of the quark-gluon plasma at even higher energy densities in the future. Whereas any experimental program at the LHC is well beyond the time scope of this Long Range Plan, an active U.S. participation in detector research and development for the LHC heavy ion program should be encouraged. The different time scales and core missions for RHIC and LHC provide opportunities for extensive international collaboration, which would be highly beneficial for both programs.

IV. FUNDAMENTAL SYMMETRIES AND NUCLEAR ASTROPHYSICS

The cross-disciplinary fields of Nuclear Astrophysics and Low-Energy Tests of Fundamental Symmetries have made enormous progress since the last Long Range Plan and continue to offer new opportunities for physics breakthroughs.

Nuclear Astrophysics

Nuclear processes played, and continue to play, a key role in the evolution of the cosmos from the original "big bang" to the complex universe of galaxies, stars and planets we inhabit today. Nuclear reaction rates determined the abundances of the elements that were produced during the "big bang". Nuclear and gravitational forces are the main power sources in our universe, providing the prodigious energies we see from stars, supernovae and the cores of galaxies. The nuclear equation of state determines the ultimate fates of stars after their nuclear fuels are exhausted. And a complex network of nuclear reactions that occur in the central cores of stars is responsible for producing the elements necessary for life to form and prosper. Thus nuclear processes have governed the chemical evolution of the galaxy since its birth.

Probably the most informative clues to the history of the universe are the abundances of the various elements. By looking at the oldest stars we learn that only, the lightest nuclei, deuterium, ^{3}He, ^{4}He and the ^{7}Li isotopes were produced in appreciable quantities from the quarks, leptons and fundamental bosons that formed the "soup" of the "big bang". One of the great triumphs of this field was the prediction (based on the neutron lifetime, the present temperature of the cosmic microwave background, three generations of light neutrinos, etc) of the abundances of the primordial light nuclei that agreed with observation. In fact, this agreement provided the first evidence that there were only three generations of light neutrinos; calculations that assumed more than three generations did not agree with the observed abundances. The prediction of the primordial abundances, together with the observed Hubble expansion and the microwave background, form the cornerstones of modern "big-bang" cosmology. This "big-bang scenario" requires that the total amount of nuclear material in the cosmos be at most $\sim$ 10% of the matter needed to eventually stop the expansion of the universe. The nature of the "missing" matter and its influence on the formation of large-scale structure in the universe is a central ingredient of one of the major unsolved problems of cosmology and astrophysics.

Nucleosynthesis

Conventional big bang nucleosynthesis theory assumes the early universe was homogeneous. Motivated by the possibility of violent phase transitions in the early universe, nuclear physicists have recently explored the consequences of inhomogeneities in the big bang and shown that, in the likely scenario, these have little effect on the matter density needed to account for the observed abundances of the very light elements. Thus the missing matter problem persists and most of the universe may consist of massive neutrinos or conjectured particles such as axions or WIMPS (weakly interacting massive particles) whose existence has been suggested by elementary particle theorists. Attempts to detect such particles in the laboratory often use nuclear techniques and exploit the properties of specific nuclei in the detectors.

Stars like our sun are essentially very large fusion reactors where hydrogen nuclei are fused into helium. The reactions usually occur at energies much too low, and temperatures much too high, to be studied in the laboratory. Therefore nuclear physicists have developed techniques for measuring reaction rates down to the lowest possible energies, usually at smaller university-based accelerators, and then extrapolating these data down to stellar energies. In our sun, the most uncertain reaction rate is that for fusing hydrogen with ^{7}Be to form ^{8}B. Several new techniques are being developed that should substantially reduce the uncertainty in this rate. A crucial test of our theories of stellar energy generation is provided by the neutrinos emitted in the fusion process. These neutrinos are the only particles that can pass directly from the center of

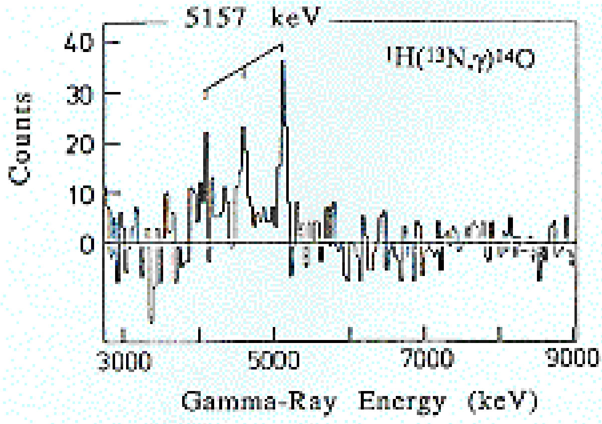

Figure IV.1 Spectrum of gamma rays produced by the fusion of protons with the radioactive nucleus ^{13}N. This is the key process for determining the astrophysical conditions under which the hot CNO cycle will operate. This spectrum was taken at a pioneering radioactive beam facility in Belgium.

the sun to the earth where they are detected as described below.

In later stages of stellar evolution, when the hydrogen fuel is exhausted, many stars fuse helium to form carbon, and then helium and carbon to form oxygen. The helium plus carbon fusion rate determines the relative amounts of carbon and oxygen in massive stars, which has a profound effect on the heavier nuclei produced when such stars explode as supernovae (see below). Despite heroic efforts, the helium plus carbon fusion rate is still very poorly known. Improving our understanding of this process is one of the key challenges in nuclear astrophysics.

In binary stars, nova explosions can occur when material from one star falls onto the surface of its companion. When temperatures and densities become high enough, protons react with unstable nuclei before they can decay, in a process known as the hot CNO cycle. The rates of most important reactions in this sequence were recently determined from laboratory measurements (see FigureIV.1).

At still higher temperatures another proton fusion sequence is initiated, producing heavier elements that are detected in the debris of nova explosions (see Fig I.A). Studies of key reactions in this sequence will be one of the important thrusts of laboratory nuclear astrophysics for the next several years.

Massive stars end their lives in spectacular explosions known as supernovae. The explosions begin with the collapse of the star's central iron core until enormous densities (about four times normal nuclear matter) are achieved. There follows a trampoline-like rebound that sends a shock wave propagating outward. The core, heated by its gravitational collapse, then cools by emitting neutrinos. Great progress has recently been made in understanding how the shock wave, the interaction of the neutrinos with matter outside the core, and the convection induced by this neutrino heating combine to create the supernova explosion.

Such supernovae are the major factories that enrich our galaxy with new elements, producing and ejecting the ashes of stellar burning (common elements like carbon, oxygen and neon) as well as many less abundant, heavier elements made in the explosion itself. One important goal of nuclear astrophysics is to combine laboratory measurements of nuclear properties and supernova theory to predict the observed abundances of heavy elements. Many of the heavy nuclei, including all the transuranic elements, are made by the rapid capture of neutrons produced in great numbers. Modelling this process requires a detailed knowledge of the properties of nuclei far from the valley of stability, many of which can be studied using radioactive beams. After many years of searching we have identified within the supernova the likely site where this synthesis occurs. A new nucleosynthesis process initiated by neutrinos in the star's mantle has also been discovered, resolving other long-standing puzzles.

A supernova explosion often leaves in its wake a *neutron star*–the compact and extemely dense remnant of the iron core composed almost entirely of neutrons. Astronomers have determined the maximum masses, cooling rates and X-ray emission rates of these stars. The explanation of these properties requires extrapolating the known properties of nuclei to radically different regimes. These extrapolations predict that neutron stars contain exotic mixed phases, such as pure neutron matter mixed with nuclear matter and even quark matter mixed with neutron matter. The superfluid properties of these mixed phases may provide an intriguing explanation for "neutron-star quakes", and are a challenge for nuclear and condensed matter theory.

The interstellar medium

The interstellar medium contains the debris of past generations of stars and is the raw material for new generations. Studies of gamma-ray

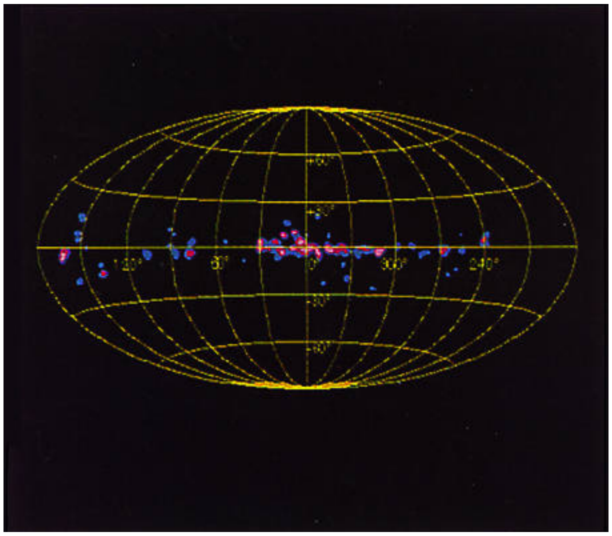

Figure IV.2 Galactic map of gamma rays emitted in decays of ^{26}Al measured by the GRO satellite. The lifetime of ^{26}Al is about 730,000 years. This map therefore shows regions of our galaxy where nuclear processes are still producing elements. Laboratory experiments determine the rates of the nuclear reactions that produce or destroy ^{26}Al.

emission from astronomical sources, cosmic-ray composition, and abundances of isotopes in meteorites provide information about the current interstellar medium and give clues about conditions prevalent within the early solar system. Satellite experiments have observed gamma rays from excited states in ^{12}C and ^{16}O in the direction of the Orion nebula, and mapped gamma emission from ^{26}Al decay in the plane of the galaxy (see Figure IV.2).

Taken together, these measurements imply that the early solar system must have been quite different from the present interstellar medium. Quantitative conclusions will require further laboratory studies of the reactions producing ^{26}Al and other very long-lived radionuclides.

Low-Energy Tests of Fundamental Symmetries

Nuclear physicists have long experience in precision, low-background measurements designed to reveal very small effects at low energy that illuminate the nature of physics at very high energies. Although the Standard Model of particle physics is consistent with all confirmed experiments, it is generally believed to be incomplete. We seek indications of how it should be extended by testing, with ever higher precision, the symmetries of that model. Current experiments probing the oscillations of solar neutrinos, family-number-violating decays of muons, and the electric dipole moments of nuclei - have reached sensitivities that exclude many candidate extensions of the standard model. Thus such experiments have great potential for discovering new physics.

Neutrino Physics

Forty years after their discovery, neutrinos remain mysterious objects. We do know that there are three types, but we still do not know their masses (except that they must be far lighter than any other fermions); we do not know if neutrinos of one type can spontaneously evolve into another type; and we do not know whether neutrinos have distinct anti-particles. If neutrinos do have non-zero masses, they would comprise at least part of the mysterious dark matter that pervades the universe.

The sun creates essentially all of its energy by fusing four protons into helium, with electron neutrinos emitted in the process. Three different pathways lead to the final state, each characterized by a distinctive energy for the electron-neutrino (the so-called *pp*, ^{7}Be, and ^{8}B neutrinos). There are now three kinds of operating solar neutrino detectors–the Kamiokande detector in Japan, the chlorine detector in the Homestake gold mine, and the SAGE and GALLEX gallium detectors in Russia and Italy respectively (all of the detector experiments have US participants). Each experiment probes a different part of the neutrino energy spectrum, and each detects fewer neutrinos than expected (see Figure IV.3). No reasonable modification of the solar models has explained the results.

On the other hand, if electron-neutrinos can evolve into other types of neutrinos that are not registered by the existing detectors, this could account for the results of all three detectors. Such “neutrino oscillations” require that neutrinos have non-zero masses. Recent observations of cosmic-ray produced neutrinos also hint that muon-type neutrinos oscillate. Confirmation of these ideas would be an important discovery.

Solar neutrino detectors now under construction, SNO (a Canadian, US, UK collaboration) and SuperKamiokande (a Japan-US collaboration), will provide information that should reveal whether or not neutrino oscillations explain the “solar neutrino puzzle”, largely independent

The Solar Neutrino Mystery

For more than a quarter of a century, one of the most intriguing puzzles in physics has been that of the “missing” solar neutrinos. Neutrinos are mysterious and elusive particles given off in many nuclear reactions, such as those that supply the sun its energy. Neutrinos are extraordinarily hard to detect because they interact so weakly with matter that almost all of the solar neutrinos hitting the earth pass completely through it. So when the first experiment designed to capture some of those solar neutrinos failed to find as many as theory predicted, many physicists assumed that the experiment was in error. Another possibility was that models of the sun used to calculate the mix of nuclear reactions and hence the expected number of neutrinos at different energies were at fault.

More careful experiments, however, merely deepened the mystery. Neither experimental error nor flawed solar models, most physicists believe, can account for the missing neutrinos. The most likely explanation appears to be that the standard theory of neutrinos themselves is inadequate. Thus, as the neutrino mystery has intensified, it has also migrated from the periphery to the core of physics.

The leading alternative to standard neutrino theory, viewed as highly speculative when it was first advanced a quarter of a century ago, is that neutrinos can transform from one kind of neutrino to another in the sun or during the 500 seconds required for them to travel from the sun to earth. Such a theory requires that neutrinos have mass — albeit very tiny amounts — overturning a longheld assumption to the contrary. That possibility intrigues astronomers working on another cosmic puzzle, the universe’s missing mass; if neutrinos do have mass, that may help explain where most of the mass of the universe resides and why astronomers can’t see it in their telescopes, even though they can

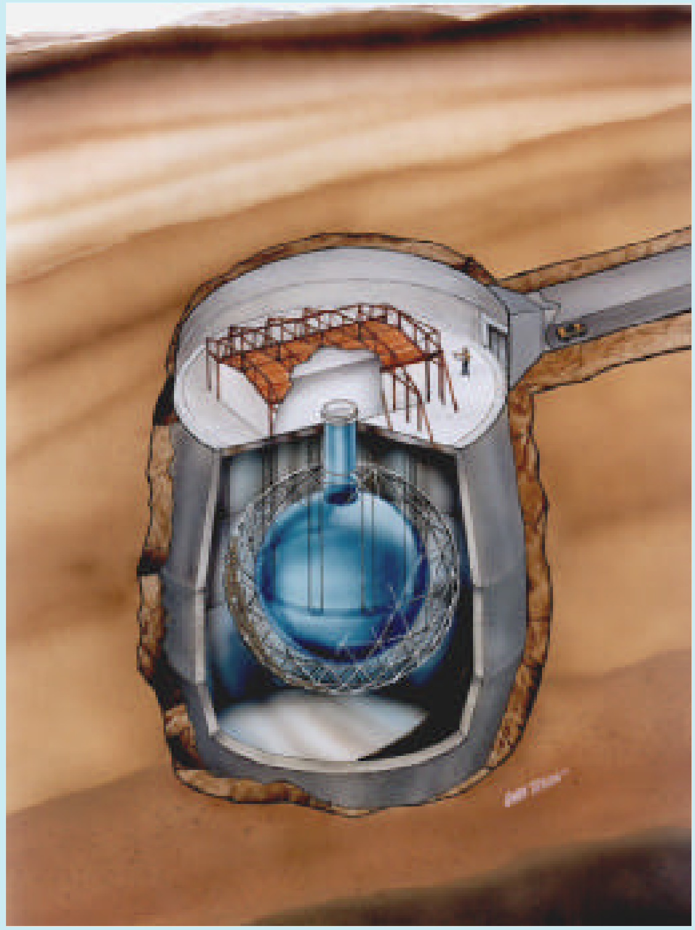

Figure IV.A The Sudbury Neutrino Observatory (SNO) under construction in Ontario, Canada. This detector is being built by a Canadian-U.S.-U.K. collaboration and will be used to determine if neutrinos coming from the sun are transforming from one kind to another.

detect its gravitational effects on the motions of galaxies.

Physicists' hopes for resolving the neutrino puzzle are vested in a new generation of experiments designed to capture neutrinos. Four such experiments are planned — one deep in a mine near Sudbury, Ontario, a second in a mine in Japan, the third in a U.S. mine, and the prototype of a fourth experiment is now operating in a tunnel underneath the Italian Alps. U.S. physicists are involved in the design and construction of all four of these experiments. The new and more sophisticated experiments are sensitive to neutrinos of different energies, permitting a more precise measurement of the spectrum of neutrinos emitted by the sun. Some of these detectors will be able to identify neutrinos that have switched from one kind to another on their flight to earth. The neutrino detectors at the core of these experiments are remarkable technological feats; they contain some of the purest materials ever made in order to reduce background radioactivity — and hence false signals — to a minimum.

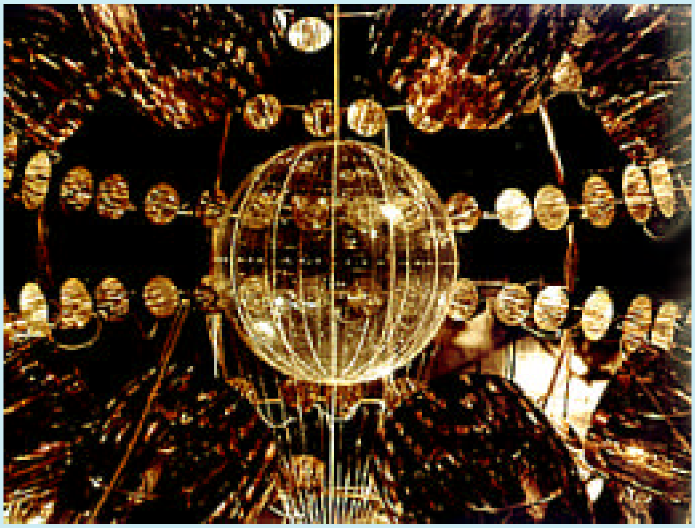

Figure IV.B View of the prototype detector developed for the Borexino solar neutrino experiment at the Gran Sasso underground laboratory in Italy. The central 2 meter diameter nylon sphere will hold 4.5 tons of liquid scintillator and is surrounded by 1000 tons of high purity water. The vessel is held down by nylon lines to balance the buoyant force resulting from the scintillator being 14% lighter than water. The light resulting from scintillation is detected with 100 8" diameter photomultiplier tubes, some of which can be seen in the photo. The experiment is being built by an Italian-German-Russian-U.S. collaboration.

If it turns out that neutrinos do have mass and do transform (oscillate) from one species to another, theorists will have to revise their "standard" description of one of the basic forces of nature. The assumption that neutrinos are massless makes for a more simple theory of the "weak" nuclear force that acts between all the constituents of matter, including neutrinos. But because there is no apparent fundamental reason why neutrinos should be massless, many physicists suspect that the solar neutrino experiments are revealing that neutrinos do indeed have very small masses.

The neutrino story illustrates the unexpected turns in science — how patient attempts over many years to study the inner workings of our sun using the most elusive particles known to physics are leading to new insights into the nature of a fundamental force.

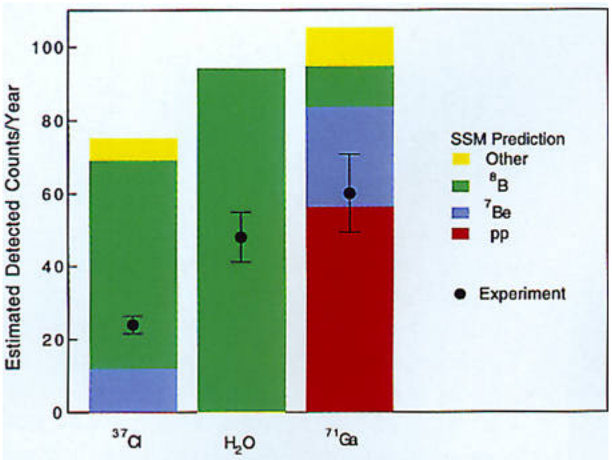

Figure IV.3 Counting rates of three types of solar neutrino detectors compared to predictions of the standard solar model. The deficits observed with all three types of detectors hint that neutrinos may spontaneously evolve from one species to another as they travel from the center of the sun.

of astrophysical uncertainties. SNO and SuperKamiokande will be able to record the energy spectrum of ^{8}B neutrinos with sufficient precision to reveal distortions induced by oscillations. In addition, SNO can distinguish the flux of electron-neutrinos from the total flux of all active neutrino species. If the total flux differs from the electron-neutrino flux, it would require new neutrino physics. Research and development on detectors with very low energy thresholds (such as Borexino, Iodine and innovative *pp* neutrino detectors) holds promise for adding a new window on the solar neutrino puzzle.

Experiments where sensitive detectors are placed up to 1 km from nuclear reactors test whether MeV electron anti-neutrinos can spontaneously evolve into other neutrino species. Two such experiments (at San Onofre and at Chooz in France), currently in preparation, should reveal whether or not the atmospheric neutrino anomaly is due to muon-neutrinos oscillating into electron neutrinos.

Accelerator-based neutrino oscillation experiments probe a different regime of neutrino masses and mixings. One of these (at Los Alamos) is supported by nuclear physics; it may have evidence for oscillations. This needs to be checked with more data at Los Alamos and at other accelerators.

Six independent studies of tritium beta decay have recently placed upper limits of 10 eV on the mass of the electron-antineutrino. The exotic process of neutrinoless double beta decay tests whether neutrinos have a mass and whether they are distinct from their antiparticles. Experiments using isotopically enriched ^{76}Ge detectors have yielded limits close to 1 eV on the masses of neutrinos that are their own antiparticle. The precise value of this limit depends on theoretical calculations of nuclear properties. Ongoing experiments should improve this limit by about a factor of five.

Symmetries in weak interactions

The neutron lifetime is one of the key parameters governing the abundances of light elements produced in the big bang. Neutron beta decay also provides crucial tests of Standard Model parameters and of possible new physics. Studies of neutron decay directly yield the weak interaction strength of the first-generation quarks. This, in combination with other weak decay measurements, constrains the existence of an additional (fourth) generation of quarks. Related efforts are made in pion and nuclear beta decays, but the the neutron decay studies are especially promising because recent improvements in cold and ultracold neutron techniques have opened up opportunities for extremely precise measurements.

Beta-decay experiments at smaller accelerators are testing the standard model prediction that relates the vector currents of the weak and electromagnetic interactions (see Figure IV.4).

Measurements of electron helicities and angular asymmetries in beta decay have been used to rule out new vector bosons (the mediators of the weak force) with masses up to the TeV range. Still other tests look for new scalar and tensor interactions. All these efforts are improving rapidly because of technical progress in the on-line production of exotic isotopes, the polarization of radioactive atoms, and confinement of atoms in traps.

The neutral-current weak charge of the nucleus is of great interest as it contains information on issues such as extra Z^0 bosons and other possible extensions to the standard model. This charge can be measured by detecting the parity-violating nucleus-electron interaction. This is best done when the electron is in a well-defined atomic bound state. Measurements of the weak charge (and the associated calculations needed to extract the charge from the measured effects) have recently reached a precision of about 1%. Several new possibilities are now available for

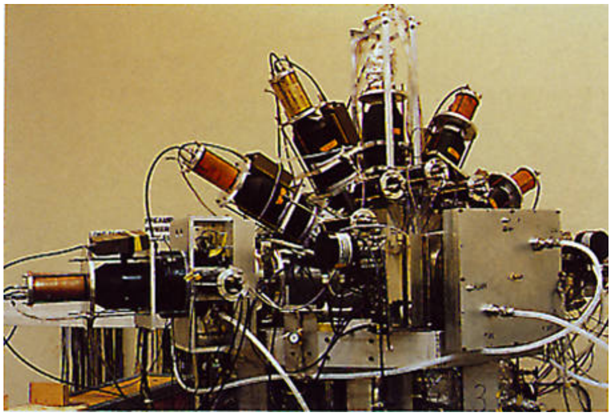

Figure IV.4 Apparatus at the University of Washington for testing fundamental symmetries in beta decay. The large black cylinders are detectors for beta particles, while the large aluminum square boxes are alpha particle detectors. This device is being used to study symmetries relating weak and electromagnetic processes, the effects of non-zero quark masses, and to search for a novel type of time-reversal violation.

improving this precision by as much as an order of magnitude, such as studying the parity-violation of single ions confined in a Penning trap, or of radioactive atoms confined in neutral atom traps. In addition, trap experiments allow one to study the weak charge of a range of isotopes of the same element–which removes many of the theoretical uncertainties in extracting the weak charge.

Time-reversal tests

Time-reversal violation has been detected only in the exquisitively sensitive decays of the neutral kaon. Understanding the origin of time-reversal violation and its connection to the baryon asymmetry in the universe is among the most important challenges in physics. Nuclear experiments test for time-reversal violating effects in the first generation of leptons and quarks. Searches for permanent electric dipole moments of neutrons, nuclei and electrons have achieved extraordinary sensitivity and provide a way to discriminate among the possible sources of time-reversal violation. For example, the standard model contains two time-reversal violating interactions–one of these is not tested in kaon decays but might be found in tests involving first-generation quarks. Many extensions of the Standard Model predict detectable dipole moments and time-reversal-violating correlations in the decays of neutrons, nuclei, and hyperons.

The experimental limits on the electric dipole moments of neutrons, electrons, and especially nuclei (such as ^{199}Hg) have improved dramatically since the last Long Range Plan. Because of the marvelous sensitivity of nuclear electric dipole experiments, nuclear theory plays a crucial role in understanding time-reversal experiments involving the first-generation quarks.

Nuclear physics techniques that push the "precision frontier" are being applied to studies of time-reversal-violating correlations in beta decay. A new neutron triple-correlation experiment is underway using cold neutrons from the NIST reactor, and improved studies of beta decays of aligned nuclei are underway at small accelerator laboratories.

Nuclear parity violation

Nuclear parity violation provides a unique window on electroweak phenomena in the presence of strong forces. The observed nucleon-nucleon parity violating amplitudes together with the (presumably) well-understood elementary quark-quark electroweak amplitudes yield information about the dynamic effects of hadronic structure on weak processes. Experiments in light nuclei have revealed that the longest-ranged component of the parity-violating nuclear interaction is much smaller than had been predicted by bag models of the nucleon. Recent QCD calculations predict effects consistent with the experimental constraints. New studies of the scattering of polarized cold neutrons by light nuclei should provide much better characterization of this interesting process. Experiments with epithermal neutrons have recently discovered many very large parity violating effects (see Figure IV.5). This work has stimulated theoretical studies of symmetry-breaking effects in statistical systems.

Weak mesonic decays

The Standard Model provides virtually no clues why nature has three versions or "generations" of the electron (e, μ and τ) that differ only by mass, or why there are three types of neutrino. Despite the apparent identity of interactions among generations, experiments seeking neutrinoless transitions of muons to electrons in the nuclear field, or muon decays to an electron and a photon, have found that such processes occur less frequently than 1 time in 10^{12}. The severe constraints imposed by these results rule out many proposed extensions of the Standard Model that postulate

When the Laws of Physics Don't Work

The laws of physics, painstakingly discovered and verified by repeated experiments, are arguably one of the finest achievements of science. Why then are physicists so interested in finding instances in which the laws are violated — or, as physicists usually put it, in which fundamental symmetries of nature are "broken"? The answer is, because discoveries of symmetry breaking often lead to new or improved laws.

Fundamental symmetries have played a key role in the development of modern physics because the identification of a symmetry is tantamount to making an assertion about a broad class of objects — the nature of some type of matter, for example, or the character of a fundamental force. By the same token, violation of a symmetry usually signifies that some important and undiscovered physics is lurking nearby — that unexpected new particles exist, or that the nature of basic forces is different than previously appreciated. Why should nature, for example, care whether things are right-handed or left-handed? The assertion that there is mirror-image symmetry (known as parity) in particle interactions seemed obvious. But in the late 1950s, it was found that parity symmetry is broken in reactions involving the weak nuclear force, and that nature did know the difference between right-handed and left-handed processes. This discovery led ultimately to the modern theory that unifies both electromagnetism and the weak nuclear force. Another basic symmetry (known as SU3 symmetry) had to do with the particles that interact via the strong force. Recognition of this symmetry inspired the quark model of matter, a central aspect of modern physics. The unexpected discovery of another symmetry in weak processes involving particles that interact via the strong force led to the prediction that there must be a fourth quark, and that the quarks occur in families, each of which has two members. We now know that there are three such families.

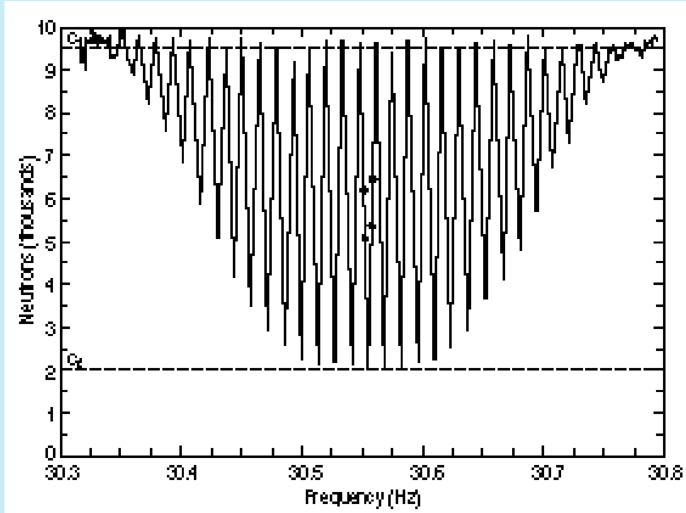

Figure IV.C Results from a high-precision search for an electric moment of the neutron. This plot shows the spin-precession frequencies of ultra-cold neutrons trapped in a bottle containing a very strong electric field. If neutrons have an electric dipole moment, the pattern will shift slightly from left to right when the direction of the field is reversed. The four dots are frequencies where data is taken. Any tiny shift will show up in the relative positions of the dots.

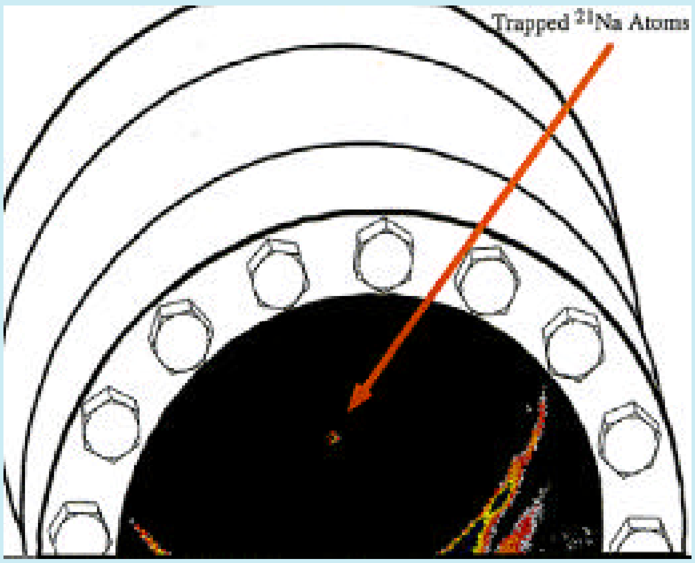

Figure IV.D Optical fluorescence from an atom "trap" at the Berkeley 88-inch cyclotron. The bright spot results from a cloud of radioactive sodium atoms held in the trap which is being developed for a study of fundamental symmetries in beta-decay. The bright areas in the lower corners are from scattered light.

A symmetry at the center of much current interest in physics is that of time reversal. In principle, this symmetry asserts, particles should not care whether time runs forward or backward. So far, only one type of phenomenon is known to violate this symmetry, but experimentalists are busy looking for others that might better indicate the sources of time reversal violation and give clues to the missing physics.

One way to look is by making exquisitely sensitive measurements of the electric fields of neutrons, electrons, and nuclei. If these particles could be shown to have permanent electric dipole moments — a separation of positive and negative charge along the particle's spin — that would be evidence of a violation of time reversal. The dipole moments, if they exist, must be a extraordinarily small, because concerted efforts have failed to find them and have placed stringent upper bounds on their sizes. For example, if the neutron were to be expanded to the size of the earth, the allowable bulge of charge at its north pole would be much much less than the thickness of a single sheet of paper. But physicists are preparing to look even more closely and measure even smaller effects.

Such experiments probe many of the phenomena of high energy physics, but require ultra-precision techniques rather than large accelerators. One leading technique is to trap radioactive atoms and study their properties. Laser beams can be used to slow (and thus cool) atoms, guide them into a weak magnetic field, and then hold the atoms in place so they can be studied with extremely high precision. The details of how the atoms decay, for example, provide a way to probe their dipole fields. With just such elegant but relatively inexpensive tools, nuclear physicists are seeking to push back the frontiers of knowledge — and to test the laws of physics in an ever more accurate fashion.

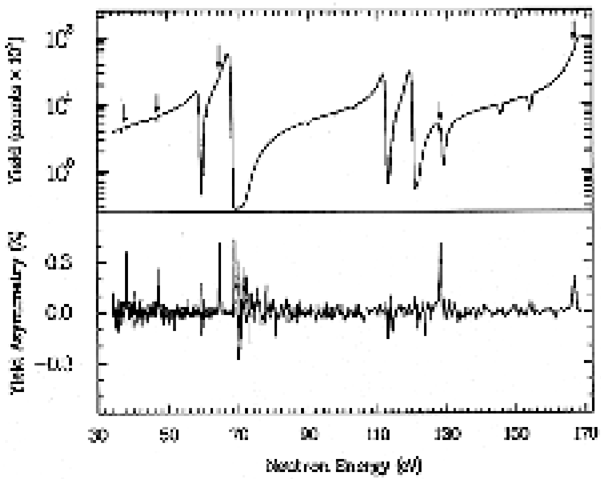

Figure IV.5 Extraordinarily large violation of mirror symmetry (parity) observed at Los Alamos. Weak interactions are known to violate parity, but the fractional violation in nuclear forces is typically less than a part per million. The upper plot shows the transmission of neutrons through a target of ^{232}Th. The large dips are caused by well-known resonances. The lower plot shows the difference in transmission for left-handed and right-handed polarized neutrons. The strikingly large differences at certain energies arise from feeble resonances that violate parity by amounts up to 10%. The mechanism for this surprisingly large enhancement is now under investigation.

new forces and particles. Precision studies of the allowed decays of muons also provide rigoroustests of the Standard Model. Technological advances are expected to yield ten-fold (or more) improvements in the power of these tests.

To continue making progress in these cross-disciplinary fields a wide variety of experimental tools is required, some of which already exist:

Nuclear astrophysicists will need ongoing access to a variety of accelerator and reactor facilities, and support for building specialized instrumentation needed to exploit these facilities. Studies focused on understanding nucleosynthesis will require accelerators capable of producing intense beams of radioactive nuclei. Theorists trying to understand the supernova mechanism and the properties of neutron stars need access to very-high-speed computers.

To successfully pursue the study of fundamental symmetries it is essential to complete and operate the SNO solar neutrino detector as well as the neutrino experiments at San Onofre and Chooz. Low-threshold neutrino detectors will be required to resolve open questions regarding solar neutrinos. Access to ultra-cold, cold, and epithermal neutron beams is essential for weak-interaction studies. Development of an ultra-cold neutron source with the world's highest intensity would open exciting new opportunities in this area. Access to intense meson beams is needed for weak decay studies. The technology for trapping atoms offers unique and highly cost-effective opportunites for precision studies as outlined above.

V. FACILITIES, INSTRUMENTATION, AND TECHNOLOGY

Introduction

As in any field of experimental science, progress in nuclear physics is intimately linked to the development of more sophisticated and higher performance instrumentation, especially particle accelerators and particle detectors. There is a continuing effort to improve the performance of these devices and to add new capabilities. During the period since the last Long Range Plan, there has been a particularly strong investment in upgrading facilities and instrumentation. Though primarily motivated by basic research, accelerators and detector techniques used by nuclear scientists have a broad range of applications outside of nuclear physics, especially in medicine and materials science. The education of young scientists, engineers and technicians is essential for the technological advancement of accelerators and instrumentation, for the progressive evolution of the field, and for meeting the nation's technological needs. The design, construction, and operation of the sophisticated devices used in nuclear research involve students at all stages. This direct participation enables the students to acquire the skills, experience, and vision to develop the next generation of particle accelerators and instrumentation for use in nuclear science and applied research, and for industrial applications.

The four frontier areas in nuclear science research are described in Chapters I-IV. A variety of complementary particle accelerators and detector systems are needed to push coherently at these frontiers, and to advance the field. In this chapter are contained brief descriptions of the experimental tools used by the nuclear physics community in the U.S., many of which have been recently developed or upgraded. The chapter is concluded with a discussion of future developments in nuclear instrumentation. In Chapter VI some examples are given of facilities outside the U.S. which are used by U.S. scientists.

Major Accelerator Facilities

Electron Accelerators

Previous LRPs have emphasized the need for electron beams with high intensity and the high duty-factor necessary for coincidence experiments. This led to the recommendations for the construction of the Continuous Electron Beam Accelerator Facility (CEBAF) and for upgrading the Bates 1-GeV accelerator through the addition of a stretcher ring. The construction of both projects is complete, commissioning is well underway, and the physics research programs are commencing.

The **Continuous Electron Beam Accelerator Facility (CEBAF)** will use electron scattering to study the hadronic structure of mesons, nucleons and nuclei. The combination of beam energy, beam intensity, high duty-factor, and sophisticated instrumentation available at this facility will open a new era for the international nuclear physics community in the high precision study of nuclear phenomena with electromagnetic probes.

CEBAF's central instrument is a superconducting (SC) continuous wave electron accelerator with an initial maximum energy of 4 GeV and 100% duty-factor. Three electron beams with a combined maximum current of 200μA can be used simultaneously for electron scattering experiments in the three experimental areas. The accelerator uses two parallel linacs based on five-cell SC niobium cavities with a nominal energy gain of 5 MeV/m. The linacs are joined by 9 isochronous magnetic arcs which allow the electron beam to be recirculated up to five times. After each of the first four passes, a transverse radio-frequency (RF) separator can be activated to extract every third bunch, and to deliver an electron beam with an energy of 1/5, 2/5, 3/5, or 4/5 of E_{max}, and 2 nsec bunch separation to one of the three experimental areas. At the end of the fifth pass, a last RF separator can split the highest energy beam into as many as three directions. The construction of the accelerator has been completed, and commissioning has started. On May 9, 1995 the accelerator reached its design energy of E_{max} = 4 GeV; the physics research program commenced in the fall of 1995.

The **Bates Linear Accelerator** at MIT provides high-quality electron beams up to an energy of 1 GeV. The pulsed linac and the isochronous recirculator provide currents in excess of 80 μA at a duty-factor of up to 1%. The existing accelerator-recirculator system feeds the recently completed South Hall Ring which will provide close to 100%-duty-factor beams. The 190-m circumference ring will operate in the energy range up to 1 GeV at peak circulating currents of up to 80 mA, and extracted currents of up to 50 μA. The ring can be operated in either pulse stretcher or storage mode. In the stretcher mode, the ring will convert the injected pulsed electron beam into a nearly continuous beam. The storage mode will be used for internal target experiments. The availability of high intensity polarized beams in the storage ring, polarized internal targets, and specialized particle detectors will add unique spin capabilities to the electronuclear program in the U.S.

Heavy Ion Accelerators

The 1989 LRP listed as its highest priority for new construction the Relativistic Heavy Ion Collider (RHIC) which is being developed at the Brookhaven National Laboratory (BNL). Construction of RHIC began in FY91 and has now passed the halfway point towards completion. Consistent with previous recommendations of the nuclear science community, the RHIC project is given the highest priority for construction in this LRP.

Apart from RHIC, the field of heavy ion accelerators has seen significant advances over the last six years at all national facilities dedicated to heavy-ion research, notably in the areas of acceleration of beams of stable nuclei in the mass region around 200, and in the production of beams of radioactive nuclei. The community has made several major advances in facility capabilities since the last LRP: the acceleration of a beam of gold ions through the Tandem-Booster-Alternating Gradient Synchrotron (AGS) accelerator complex at Brookhaven; the production and isotopic separation of radioactive beams via the fragmentation method using the K1200 SC cyclotron at Michigan State University (MSU); the completion of the uranium-beam upgrade of the superconducting heavy-ion accelerator (ATLAS) at Argonne National Laboratory to provide intense, high-quality beams of heavy nuclei up to uranium with 100% duty cycle; the conversion of the Holifield Heavy Ion Research Facility at ORNL to a radioactive ion beam facility, and the successful operation of the LBL 88″ Cyclotron with an advanced ECR ion source to provide stable beams for experiments with the Gammasphere multi-detector photon detector.

The **Relativistic Heavy-Ion Collider (RHIC)** will be able to collide beams of any nuclear species at center-of-mass energies up to 200 GeV per nucleon pair for the heaviest nuclei. RHIC's scientific goal is to search for and study the quark-gluon plasma (QGP). Collisions of protons with heavy nuclei, as well as collisions of protons with protons will also be possible. The protons can be longitudinally or transversely polarized. Average luminosities of $2 \times 10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for Au-Au collisions and up to $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for p-p collisions are expected. RHIC consists of two rings of SC dipole and quadrupole magnets together with RF accelerating systems, corrector magnets, vacuum and control systems. Collision areas for four experiments are being prepared, with two more areas available for future development. Completion of RHIC construction and commissioning is foreseen for early 1999. About twice a day, the Tandem-Booster-AGS complex will be used for about one hour to fill RHIC. Thus, if the scientific priorities are sufficiently high, a fixed target heavy-ion program or secondary hadron-beam program using protons, pions and/or kaons can continue at the AGS during the operation of RHIC.

The **Tandem/AGS** facility at the BNL is presently the highest energy heavy-ion accelerator in the U.S., and provides beams of relativistic heavy ions of up to 14.6 GeV/nucleon for nuclear physics research. Ions are accelerated in the Tandem Van de Graaff and injected into the AGS Booster. Fully-stripped ions are then injected into the AGS where they are further accelerated. Beams of ^{197}Au ions were accelerated for experiments for the first time in 1992. At present, there are six major experiments on the AGS floor, concentrating on particle spectra and correlations, energy-flow measurements, strangeness production and multi-particle correlations, and the search for multiply strange objects and exotic new particles.

The **National Superconducting Cyclotron Laboratory (NSCL)** at Michigan State University is the main intermediate-energy heavy-ion user facility in the U.S. The nuclear physics research covers the exploration of nuclear matter at high temperatures and densities, and the exploration of nuclei with extreme ratios of neutrons to protons. This latter direction of research is currently undergoing a rapid expansion worldwide due to the recent availability of beams of short-lived nuclear species ("radioactive beams"). The NSCL operates the largest SC cyclotron in the world, the K1200. It provides high quality beams, including 200 MeV protons, 1.6 GeV oxygen, 12.9 GeV krypton, and 5.9 GeV uranium ions. A SC Electron Cyclotron Resonance (ECR) ion source allows the production of highly charged ions needed for operation at the highest energy. A room-temperature ECR ion source produces intense ion beams of lower charge state needed for experiments with radioactive beams. A new SC beam analysis system, the A1200, provides for efficient separation of radioactive beams produced in projectile-fragmentation reactions. A SC beam transport system, installed behind the A1200, transports both stable and radioactive beams to the experimental areas. The NSCL has proposed to couple its existing K500 and K1200 cyclotrons, and thus enhance greatly the performance of the facility, particularly for studies with radioactive beams.

The **Argonne Tandem-Linac Accelerator System (ATLAS)** at Argonne National Laboratory consists of a superconducting linear accelerator, which is injected by either a 9-MV Tandem Van de Graaff or a new positive-ion injector (PII) consisting of an ECR ion source and a SC injector linac of novel design. Using the PII, ATLAS now routinely accelerates intense beams up to uranium with energies up to 20 MeV/nucleon and with excellent beam properties. The accelerator has 100% duty cycle and is ideal for high-resolution heavy-ion nuclear physics research where nuclear structure effects are particularly important. ATLAS can also provide very short beam pulses ($<$150 psec), a feature that has opened new research opportunities. The present experimental program at ATLAS addresses the study of nuclear structure at the extremes of nuclear behavior, including nuclei at high spin, exotic nuclei at the limits of stability and reactions important to nuclear astrophysics and nucleosynthesis. Other programs include the development of ultra-low detection capabilities for heavy radioisotopes (accelerator mass spectrometry), the study of atomic physics of highly-stripped atoms, and the application of nuclear techniques to material research. Major equipment includes a multi-detector gamma-ray system, two magnetic spectrographs and a fragment mass analyzer (FMA) with better than unit mass resolution and with excellent beam suppression at zero degrees of better than 1 in 10^{12}. A two solenoid spectrometer (APEX) was recently completed to study positrons produced by supercritical electromagnetic fields transiently created in collisions of two very heavy nuclei.

The **Holifield Radioactive Ion Beam Facility (HRIBF)** is presently under construction at Oak Ridge National Laboratory to permit research with precisely-controlled beams of radioactive nuclei generated by the ISOL (isotope separator on-line) technique. Light ions (p,d,^{3}He,α) accelerated by the Oak Ridge Isochronous Cyclotron strike an isotope-production target. Radioactive atoms produced in the target are extracted, ionized, mass selected, charge exchanged, pre-accelerated, and injected into a 25 MV tandem electrostatic accelerator for acceleration to final energies. The novel and unique ion beams are being used to study nuclear structure far from stability and reactions of interest to nuclear astrophysics. Experimental apparatus includes a high-resolution split-pole magnetic spectrometer and a 72-element, 4π NaI γ-ray detector (Spin Spectrometer). A recoil mass spectrometer (RMS) of new design, highly-segmented arrays of Ge γ-ray and charged-particle detectors, and a recoil separator optimized as a velocity filter are in use at two new end stations.

The **88″ Cyclotron** at the Lawrence Berkeley Laboratory is a variable-energy isochronous cyclotron with spiral-sector focusing. A new ECR source, operating at 14 GHz, provides ion beams at the Coulomb barrier up to A$=200$ as well as light ions with energies up to 35 MeV/nucleon. Experimental programs are carried out in nuclear science as well as in atomic physics, surface physics, radiation damage in semiconductors, and biomedicine. The nuclear research program is focused on investigations of heavy-ion reaction mechanisms, production and study of exotic nuclei far from stability, structure at high angular momenta, nuclear astrophysics, and the chemical and physical properties of the transuranic elements. The Gammasphere photon detector has been operating in an early implementation mode at the 88″ Cyclotron; the detector now includes over 80 (of a total of 110) of its large volume Ge detectors and associated Compton suppressors.

Proton Accelerators

The **Indiana University Cyclotron Facility (IUCF)** is one of the two major nuclear facilities that are supported by the National Science

Foundation. Polarized and unpolarized light ion beams are accelerated to 200 Z^2/A MeV by a coupled pair of separated sector cyclotrons. The beam can also be injected into the Cooler, a synchrotron and storage ring, where it is further accelerated up to 470 Z^2/A MeV. Electron cooling in the ring provides beams of exceptionally small spatial extent for studies in accelerator physics, and for nuclear physics experiments, e.g. the study of threshold phenomena. Electron cooling also compensates for heating in internal target nuclear physics experiments. A new high intensity polarized ion source and pre-injector are now operational and provide injection currents of up to 200 μA. A 7 MeV RFQ + Linac and 200 MeV synchrotron is under construction. This will greatly increase the efficiency of filling the Cooler, and stored beams of up to 20 mA are anticipated.

The H^+ beam of the former LAMPF 800-MeV proton linac produces intense secondary beams of pions, muons, and neutrinos. At the same time, pulses of H^- ions are used to produce a white neutron spectrum at the WNR (Weapons Neutron Research) facility, and are injected into the high-current proton storage ring (PSR) that feeds the **LANSCE** (Los Alamos Neutron Science Center) pulsed spallation neutron source. Starting in FY96, the DOE Office of Defense Programs will operate the linac with the purpose of pursuing basic and applied neutron physics. High-priority nuclear physics experiments can still be pursued at the linac in a cost-effective way. Examples include the continued running of the LSND (Liquid Scintillator Neutrino Detector) experiment, as well as the operation of an ultra-cold neutron source based on the present LANSCE source.

Nuclear experiments with hadrons use primary beams of protons and secondary beams at the Alternating Gradient Synchrotron (AGS) at BNL and at the Fermi National Accelerator Laboratory (FNAL) in Illinois. The resulting experimental program covers a broad range of topics. Typical examples are: production and spectroscopy of hypernuclei, searching for H-particle production, measuring the g-factor of the muon, searching for rare decay modes of the K^+ meson (AGS), and measurements of the quark and antiquark distributions in nuclei by means of muon scattering and Drell-Yan muon-pair production (FNAL).

University Accelerator Laboratories

Smaller accelerators serve the important function of providing specialized capabilities which cannot be met by the larger national user facilities. Examples of problems requiring lower beam energies and thus smaller accelerators are: studies of parity violation in light nuclei, reactions near the Coulomb barrier, or the study of nuclear reactions that are relevant to astrophysics, such as the hot CNO cycle.

At present eight small accelerators are supported by NSF/DOE. These are situated on university campuses and serve not only local faculty and students, but are often used by visitors who take advantage of their unique capabilities. In most cases, the capabilities of these machines result from intensive, sometimes even speculative, development work on new instrumentation, such as novel detectors or ion sources. The modest cost of accelerator operation and the availability of the accelerator over long periods of time permit equipment development that could not be carried out in a cost effective way on large machines. The resulting technology has often led to improvements of the corresponding instrumentation at larger accelerators. Not only do these laboratories provide essential tools for nuclear science at modest cost, but their visible presence on campus serves to attract graduate students both to nuclear physics and also to accelerator science.

The accelerators at Florida State University, S.U.N.Y at Stony Brook, and the University of Washington consist of tandem electrostatic accelerators coupled to SC linear accelerators to augment their energy. At Florida State University, polarized Li ions are produced by laser pumping, and are used to study spin effects in elastic and inelastic processes. New capabilities at Stony Brook include the development of a magneto-optical trap for production and trapping of short-lived radioactive nuclei. The accelerator at the University of Washington has been equipped with a new ion source in the tandem terminal to provide the intense beams of alpha particles required for new weak interaction studies.

The early work on production of radioactive beams at the University of Notre Dame led to systematic studies with ^{8}Li of importance in cosmology. A new beam analysis system and spectrometer at Texas A&M University coupled to the SC cyclotron provides radioactive beam capabilities for studies of exotic nuclei and astrophysics. The large tandem accelerator at Yale University which has been used to accelerate heavy ions of mass up to Au, is being augmented with a mass separator facility in the terminal of the machine for use in nuclear structure and nuclear astrophysics programs.

The availability of polarized beams of protons and deuterons at the Triangle Universities Nuclear Laboratory, TUNL, and at the University of Wisconsin is of importance to studies of few-body systems. The development of polarized gas targets at Wisconsin and of polarized ion sources and solid polarized targets at TUNL, which has important applications to the research programs at large accelerators, exemplifies the symbiotic relationship between small university accelerators and the large national and international facilities.

Other Facilities

Important nuclear physics experiments are carried out at facilities that are operated primarily by other branches of physics or by foreign countries (see Chapter VI).

The **Laser Electron Gamma Source (LEGS)** at the Brookhaven National Synchrotron Light Source has been producing tagged polarized gamma rays since 1990. Until the fall of 1994, energies have been limited to 330 MeV. Recent upgrades, in both the electron ring and in the laser, will increase the maximum gamma ray energy to 470 MeV. Capitalizing on the high degree of beam polarization, experiments have provided precise constraints on the short range part of the N-N tensor interaction. The future experimental program at LEGS will focus on measurements on the nucleon using both polarized beams and targets.

In the U.S., regulatory action has led to the suspension of operations at most large research and production reactors, but the High Flux Beam Reactor at Brookhaven and the Missouri University Research Reactor continue to be available both for neutron activation and for neutron-based nuclear structure physics.

Spallation sources at Los Alamos (LANSCE) and at Argonne (IPNS) have provided a broad spectrum of neutrons for basic and applied research, and represent the only practical sources of epithermal neutrons. At LANSCE, experiments on hadronic parity violation (PV) could be carried out in “current mode”, i.e., the beam is so intense that PV signals could be recorded as a continuous ion-chamber current. The IPNS source was used as a test-bed for production of ultra-cold neutrons (UCN); this technology will be further developed at LANSCE. The pulse structure of spallation sources is often a distinct experimental advantage.

The recently upgraded NBS Reactor at Gaithersburg incorporates a cold liquid hydrogen moderator, and delivers high-quality cold neutron beams to a new guide hall. Experiments on the neutron half-life and correlation coefficients, time-reversal invariance violation, parity-violating spin rotation, and neutron interferometry are in progress.

Detectors for Nuclear Physics Experiments

Since the last LRP, important detector developments have taken place, ranging from the search for new detector concepts to the design and construction of large detector systems (both in physical size and in the number of read-out channels). Major trends are increases in solid angle coverage, and improvements in resolution and data acquisition speed. In the following sections, the main features of new detection systems used to pursue questions in the different physics categories of this LRP will be described.

Detectors for the Study of Fundamental Symmetries and Nuclear Astrophysics

There are at present four operating solar neutrino detectors, the Cl-Ar experiment in the Homestake gold mine (South Dakota), Kamiokande-III in the Kamioka mine (Japan), the SAGE gallium detector in the Baksan Laboratory (Russia), and the Gallex gallium detector in Gran Sasso (Italy). In addition, four new detectors are in an advanced state of preparation: the Sudbury Neutrino Observatory, SNO, (Ontario), SuperKamiokande (Japan), Borexino in Gran Sasso, and the Iodine experiment in the Homestake mine. This makes it very likely that a conclusive resolution of the solar neutrino problem will be reached in the near future, a marked change from the situation 10, or even 5 years ago.

The 200-ton Liquid Scintillator Neutrino Detector, LSND, at Los Alamos detects both scintillation and Cerenkov light to identify the different neutrino-interaction processes; it has recently yielded preliminary evidence consistent with a neutrino oscillation signal. Two smaller scintillation detectors for reactor anti-neutrinos are being constructed at the San Onofre reactor complex in California, and at the new Chooz reactor complex in France.

The search for high-energy cosmic-rays from point sources is conducted with a wide range of detectors all over the world. The Cygnus and Milagro arrays at Los Alamos are designed to cover the critical intermediate-energy regime of 0.1 to 10 TeV that previously has not been instrumented sufficiently well for point sources to be detected. Milagro makes use of a large water storage pond in the Jemez mountains above Los Alamos.

Detectors for Nuclear Structure Studies

The Gammasphere photon detector array consists of 110 large Compton-suppressed germanium crystals; it has a very high efficiency and energy resolution for gamma rays in the energy range from l0 keV to 10 MeV. Gammasphere is being constructed and used in experiments at the Lawrence Berkeley Laboratory. Once completed, it will be stationed in turn at several accelerator laboratories to make optimum use of its capabilities. Its partial implementation has already been used in 60 experiments, yielding new insights into the nucleus at high spin and high deformation.

At the National Superconducting Cyclotron Laboratory (NSCL), the S800 SC spectrograph is nearing completion. The S800 is a large solid angle (10-20 msr), large momentum acceptance, high resolution (δp/p = 10^{-4}) spectrometer. It will be capable of resolving final states in nuclear collisions even at the high energies of the primary and radioactive beams from the present NSCL K1200 cyclotron and the future coupled cyclotrons. The S800 will be used for studies of giant resonances, astrophysics, nuclei far from stability, and reaction mechanisms.

At the Indiana University Cyclotron Facility (IUCF), the K600 spectrograph has been setting unparalleled resolution benchmarks. It has been equipped with a focal plane polarimeter and a septum entrance magnet for small angle operation. Extensive development has made possible inelastic scattering experiments at zero degrees. With the recent completion of a second port for scattered proton polarimetry, it is now possible to measure all spin observables for proton-proton scattering. Future experimental efforts will concentrate on spin observables as the key to a better understanding of the free NN interaction, and tests of medium modifications to the interaction expected from relativistic and QCD-inspired models.

The detection of neutral mesons with high resolution and efficiency has been a long standing technological challenge. The NMS (Neutral Meson Spectrometer), built at Los Alamos National Laboratory and soon to be moved to BNL, is the the world's premier detector for π^0 and η mesons. Its two arms detect the high energy decay photons with BGO converters and pure CsI calorimeters. The NMS has a large solid angle of 3.7 msr, and has achieved an energy resolution for π^0 of less than 800 keV.

Detectors to Study the Quark Structure of Matter

At CEBAF, three experimental areas, halls A, B, and C contain complementary equipment to cover a wide range of physics problems.

Hall C houses two magnetic spectrometers: the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS). The HMS is a QQQD spectrometer for momenta up to 7 GeV/c with iron dominated quadrupoles and a homogenous field dipole; all HMS magnets use SC coils. The SOS is a normal-conducting QDD spectrometer with a maximum central momentum of 1.5 GeV/c and a short path length, which permits efficient detection of short-lived particles.

Hall A instrumentation consists of two 4-GeV/c magnetic spectrometers (HRS) with an unprecedented combination of resolution, solid angle, and momentum range. The QQDQ design gives a momentum resolution of 10^{-4} in a solid angle of 8 msr and in a 10% momentum bite. The tracking part of the detector systems is identical for both spectrometers; the particle identification part is specialized for electrons in one spectrometer and for hadrons in the other. The hadron arm is also equipped with a focal plane polarimeter to measure the polarization of protons.

Hall B's main instrument is the CEBAF Large Acceptance Spectrometer, CLAS; its magnetic field is generated by a six-coil, iron-free SC torus. The particle detection system consists of drift chambers to determine the trajectories of charged particles, Cerenkov counters for the identification of electrons, scintillation counters for the trigger and for time-of-flight measurements, and electromagnetic calorimeters to identify electrons and to detect photons and neutrons.

At the MIT/Bates accelerator, new capabilities are being added to the standard magnetic spectrometers (ELSSY, MEPS, and OHIPS). A set of four magnetic spectrometers is being built that can be moved out of the electron scattering plane. This allows several new structure functions to be determined that are sensitive to interference terms. A focal plane polarimeter has been added to the OHIPS instrumentation to study the proton polarization in $(e, e'\vec{p})$ and $(\vec{e}, e'\vec{p})$ reactions.

The SAMPLE experiment at Bates studies the parity violating asymmetry in the scattering of polarized electrons off the proton with the goal to determine the proton's strange quark content. Backward scattered electrons are detected in a large solid angle air Cerenkov detector.

A large acceptance magnetic spectrometer, BLAST (Bates Large Acceptance Spectrometer), has been proposed to exploit the capability of the South Hall Ring to perform experiments with polarized internal targets.

Detectors to Study the Phases of Nuclear Matter

At the National Superconducting Cyclotron Laboratory (NSCL), two highly segmented charged particle arrays are used to characterize the particles emitted in heavy ion collisions at intermediate energies. The 4π-array consists of 30 position sensitive parallel-plate detectors, backed by segmented Bragg ionization chambers and an array of 215 phoswich detectors, each consisting of a fast-slow plastic scintillator combination. The 4π array is capable of detecting particles ranging from fission fragments at E/A = 1 MeV to 220 MeV protons, even if they are traveling in the same direction. A multi-node transputer system was recently added to the data acquisition hardware to allow real time data filtering and elimination of unwanted background.

The Miniball multi-fragment detection array is a low threshold 4π-plastic-scintillator-CsI(Tl) phoswich detector. It can be operated in the target chamber of the S800 spectrograph. The large angle and energy coverage will allow characterization of collisions on an event-by-event basis. The Miniball is often mounted inside the Superball to allow simultaneous 4π coverage of neutrons and charged particles. The Superball is a high-efficiency neutron multiplicity meter containing $\approx$17m^3 of Gd-doped scintillator.

At the AGS, collisions of relativistic heavy ions such as gold with heavy targets provide very large compression of the projectile and target nuclei. At sufficiently high energy and at small impact parameter, novel forms of nuclear matter may be produced, e.g., conglomerates rich in strange quarks. The first run of experiment E864 to search for such exotic objects has just been completed. Experiment E866, consisting of two magnetic spectrometers, is designed to study particle production in relativistic Au-Au collisions at 10 GeV per nucleon.

The RHIC detectors collectively cover all of the predicted signatures for the QGP. There are two complementary major detector systems, PHENIX and STAR (both well into the construction) and two smaller-scale detector systems, PHOBOS and BRAHMS.

The STAR detector uses the large solid angle tracking and particle identification capability of a cylindrical Time Projection Chamber (TPC), placed in a large solenoidal magnet. The design emphasizes detection of the global features of the hadrons (soft processes) and jets (hard scattering processes) as the signatures for QGP formation. Proposed additions to this detector include a Silicon Vertex Tracker, an electromagnetic calorimeter, a time-of-flight array covering about one-third of the solid angle subtended by the TPC, and a pair of external TPC's.

The PHENIX detector focuses on the detection of leptons, photons, and hadrons in selected solid angles, with a high rate capability, to emphasize the electromagnetic signatures of QGP formation. The central part of PHENIX consists of an axial field magnet and two detector arms, each covering the rapidity region of $|\eta| \leq$0.35 and 1/4 of the full azimuth. Each arm will be equipped with a drift chamber, pad chambers, ring imaging Cerenkov counter, time expansion chamber, time-of-flight, and electromagnetic calorimeters. Silicon detectors close to the beam pipe provide close to 4π-coverage for particle detection. Upgrade items proposed for PHENIX are the instrumentation for the forward muon arm, a high resolution photon detector, and improved tracking and trigger electronics.

PHOBOS is a true table-top detector; its double arm spectrometers use small magnets with strong magnetic fields and high spatial resolution silicon detector planes. The detector focuses on hadronic signatures for the QGP at low transverse momentum. BRAHMS uses two independent magnetic spectrometer arms for inclusive measurements with particle identification, and is able to reach very forward angles, well into the fragmentation region.

Accelerator Technology

Ion Sources

Large gains in the yield of Electron Cyclotron Resonance ion sources have been achieved due to the operation at higher magnetic field (the superconducting SC-ECR at the NSCL), or higher field and frequency (LBL Advanced ECR). Beams of Bi^{41+} and U^{42+} at $1 \mu A$ and O^{6+} at 400 μA have been demonstrated. New or upgraded sources are under development at Texas A&M, ATLAS, and LBL; they incorporate enhanced magnetic field confinement, higher frequency, and external sources of cold electrons. Improvements in oven technology and new techniques such as biased probe sputtering have made beams of virtually any element possible. ECR sources are critical components for the production of radioactive beams.

The efficient production of beams of radioactive ions using the isotope separator on-line (ISOL) technique has progressed significantly. In this method radioactive atoms are produced by a nuclear reaction in a hot target and, after diffusion, are ionized and mass selected. Very low energy beams of 10 particle nanoamperes or more have been demonstrated by the ISOLDE facility at CERN using this technique, which is the basis of the HRIBF (slated to become operational at ORNL this year). Additional R+D will be required (see below) to make this type of ion source capable of satisfying the specifications for a National ISOL Facility (discussed in recommmendation 3 and Chapter I).

Polarized Beams and Targets

Measurements of polarization degrees of freedom play an increasing role for nuclear physics. Due to interference effects, polarization measurements are sensitive to reaction amplitudes that are too small to be accessed directly in cross section measurements.

Since the last LRP, dramatic progress has been made in the development of polarized electron sources with a high degree of polarization and high average beam currents. As an example, SLAC developed a laser driven strained GaAs photocathode to produce an electron beam with ≈85% polarization and an average current of several micro-amperes, which was used in experiment E142 to determine the spin structure function of the nucleon in the deep inelastic region.

Progress in the production of intense polarized beams has continued on two fronts. Experiments at PSI (Switzerland), Saclay (France), and TUNL have shown that improved ionizers can achieve high ionization efficiency of atoms produced by the atomic-beam method. The highest intensity beams now available are produced by recent improvements in the laser optical-pumping technique at TRIUMF (Canada), KEK (Japan), and INR (Russia), leading to pulsed currents well above 1 mA. A source of polarized light negative ions (Li, Na) for injection into tandem accelerators is in use at Florida State University.

Many experiments on electroweak interactions and fundamental symmetries require beams of polarized neutrons. An established art is the production of very highly polarized (>98%) cold neutrons by "supermirrors" (multi-layer magnetized films that preferentially reflect neutrons of one polarization). A promising new method, being developed at the University of Michigan and at NIST is the spin-dependent absorption of neutrons in a polarized ^{3}He absorber. Experiments in parity violation and time-reversal violation at epithermal energies have employed a different technique, the scattering of neutrons from polarized protons. At the very lowest energies, ultracold neutrons can be polarized with essentially 100% polarization by "brute force" in a magnetic field.

Future uses of polarized protons in the RHIC and LISS storage rings depend on the development of methods to avoid the effect of depolarizing resonances created by the magnetic fields of the storage rings. Spin precessors have been shown to overcome this problem, as demonstrated strikingly in experiments carried out at the IUCF proton storage ring. In addition, means have been developed that permit the spin of the stored protons to be reversed rapidly with less than 2% loss in polarization.

Major progress has been achieved toward the use of highly polarized gas targets of hydrogen and deuterium in storage rings. A Wisconsin-Heidelberg collaboration has developed a new, high intensity atomic-beam apparatus for injection of polarized atoms into a target cell, and showed that a target of 10^{14} atoms/cm^2 with polarization of 80% survives bombardment by intense beams in a test storage ring. This apparatus will provide the polarized hydrogen target for the HERMES experiment. A second target built at Wisconsin and installed in the IUCF storage ring proved the feasibility of high accuracy spin correlation experiments. Earlier results on scattering of electrons obtained with a deuterium target cell at Novosibirsk have recently been augmented by measurements with a much improved target at NIKHEF. Significant improvement in target density from the use of spin-exchange optical pumping of deuterium has been reported by ANL.

Production of polarized ^{3}He gas targets has made important progress, both for low density targets in storage rings and high density targets for use in external beams of protons, pions, and electrons. Use of a polarized ^{3}He target in the IUCF proton storage ring demonstrated for the first time the advantages of internal targets for spin correlation experiments. The HERMES polarized ^{3}He target operated at an average polarization of 47% and a thickness of 10^{15} nucleons/cm^2 over the 1995 data taking period. The target polarization was determined both by measurements on the atoms directed to the target cell, and independently by detection of the beam-induced excitation of the atoms in the target cell. High density targets with pressures of some 10 atm and polarization as high as 60% have been the basis of important new experiments at SLAC, TRIUMF, and Mainz.

The more conventional polarized solid targets continue to improve: high degree of polarization and improved radiation resistance for protons, e.g., in beads of frozen ammonia, tensor polarized deuterium in LiD, and improved methods of spin reversal in frozen-spin targets. A novel frozen-spin polarized target, SPHICE (Strongly Polarized Hydrogen ICE), consisting of molecular HD in the solid phase, is being developed for experiments at LEGS.

Acceleration Structures

Advances in SC RF technology have allowed the large scale production of SC cavities that operate reliably at high field gradients. The CEBAF accelerator that employs 338 five-cell Nb cavities has recently been completed, and has reached its design energy of 4 GeV. CEBAF cavities operate at a temperature of 2 K and a frequency of 1.5 GHz. The average gradient achieved in cavity tests is close to 10 MeV/m, giving rise to the expectation that the accelerator will be able to reach 6 GeV with only minor hardware upgrades. Lower-frequency SC cavities are in routine use at heavy-ion accelerators. A challenge has been to develop resonators capable of accelerating very heavy ions and extending SC accelerating structures to very low velocities. The PII at the ATLAS facility has succeeded in lowering the velocity limit by a factor of five.

Superconducting Magnets

Superconducting magnets have become increasingly important for nuclear physics instrumentation, especially for sources, accelerators, and magnetic spectrometers.

RHIC dipole and quadrupole magnets are of the cold-iron, collared-coil type with a single-layer Nb-Ti SC cable stabilized with Cu. The dipole magnets produce 4 Tesla at full excitation. Following initial development and prototype work at BNL, the magnet production technology was transferred to industry. All magnets produced have met design specifications. The field quality is so high that the magnets can be installed directly into the accelerator without an extensive selection process.

At the National Superconducting Cyclotron Laboratory (NSCL), the K1200 cyclotron is followed by the A1200 SC magnetic analysis system with a solid angle $\Delta\Omega = 2.2$ msr and a momentum resolution $p/\delta p \approx 2000$.

At CEBAF, SC magnets are used in all three experimental areas. The 4-GeV/c spectrometers in Hall A use large diameter cos(2Θ) quadrupoles with higher order correction windings, and an iron-dominated dipole magnet with curved entrance and exit faces. The Hall C High Momentum Spectrometer, HMS, is using cold-iron quadrupoles with SC windings followed by a SC dipole magnet. Hall B's magnetic multi-gap spectrometer CLAS is based on an iron-free toroidal magnet with six SC coils.

Computing and Information

The development of computer technology in the past decades has had a profound impact on nuclear physics. On the experimental side, it has made possible the accumulation and manipulation of large bodies of data. Experiments at the new facilities, especially at CEBAF and RHIC, will operate at even higher data acquisition rates. These experiments will require

Computing How Quarks Behave

One of the peculiarities of modern physics is that the most basic constituents of matter — particles known as quarks — can never be observed directly. 'Naked' quarks simply never appear, even at the highest energies obtainable by powerful accelerators. Instead physicists have had to infer their properties from the behavior of particles which result when quarks are combined — the familiar protons, neutrons, and mesons of nuclear physics.

To really understand the structure of matter, however, and to be able to predict its properties under the extreme conditions found in such astrophysical phenomena as neutron stars or supernovae, requires a more precise understanding how nuclear forces 'confine' quarks and how quarks interact to create the substructure of protons, neutrons and atomic nuclei. A promising approach is to use the power of modern high-performance computers to calculate this substructure of matter directly.

Although the equations which must be solved are known, computing how quarks behave is much more difficult than its atomic equivalent. Within atoms, for example, electrons interact by exchanging photons — particles of light — but the photons don't interact with each other. This allows physicists to approximate the answer, then make repeated corrections until high accuracy is obtained. Within a proton or neutron, however, quarks interact by exchanging particles known as gluons which also interact strongly with each other. That property immensely complicates the calculation so that a novel approach and vastly larger amounts of computation are required.

The approach which has now been shown to work is based on a formulation of quantum mechanics by the late American physicist Richard Feynman, which expresses the solution to a problem as the

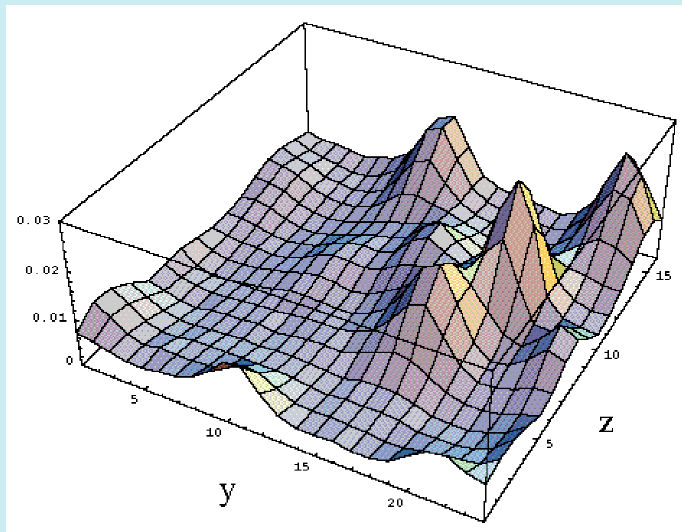

Figure V.A   Five "lumps" in the gluon field, as calculated on a large supercomputer, corresponding to typical vortex-like excitations. These structures play an influential role in determining the behavior of the quarks inside protons and neutrons.

sum over all of the possible time histories that a system can undergo. This sum can be computed approximately to any desired precision by sampling a sufficiently large number of these different time histories. This approach is ideally suited to massively parallel computers, in which hundreds of processors work together simultaneously, but independently.

Nonetheless, the computational demands are immense. Realistic calculations often entail over a billion variables. One such effort has required months of time at a powerful supercomputer with 1024 processors at the Los Alamos National Laboratory; others have fully occupied smaller, special purpose computers for several years on a single problem.

One insight into subnuclear structure already gained from such calculations has to do with the behavior of the gluon fields within a particle such as a proton — fields which cannot be observed directly. Calculations of such gluon fields show phenomena similar to the vortices observed in fluids (like the eddies behind a canoe paddle) — structures which are responsible for essential features of the observed particles.

Advances in the speed of massively parallel computers would lead to advances in the ability to compute the fundamental structure of matter. Indeed, such computational approaches are the only way to get at the detailed behavior of quarks and the structure of nuclei — and hence to fully understand the physics of phenomena that can't be reproduced in the laboratory but that are prominent features of our world. One such target is nuclear reactions in the sun, some of which are now within the reach of today's computers. An even more tantalizing possibility, to astrophysicists, is the exotic nuclear matter found in neutron stars. That, however, will have to await still more powerful machines.

Figure V.B Large magnetic coils for CLAS, the novel detector which will permit new experimental studies of how quarks behave in nuclei when energy is delivered to protons and neutrons by the CEBAF electron beam.

high data transfer rate to permanent storage (≥ 10 Mbyte/sec), substantial compute power for off-line analysis (≥ 10 Gflops), and robotic access to large amounts of stored data (≥ 100 Tbytes). In addition, large bandwidth, wide-area computer networks will be required so that outside user groups at the larger facilities are able to participate in the data analysis from their home institutions.

On the theoretical side, the increase in compute power has enabled extensive calculations and model building, both analytical and numerical, that would have been otherwise impossible. Examples include lattice-gauge calculations, Monte Carlo treatment of finite nuclei, and simulations of complex heavy-ion collisions.

The Nuclear Data Program provides access to *evaluated* nuclear-reaction and nuclear-structure data, which is important to the nation in such areas as nuclear power, national security, medicine, industrial applications, nuclear waste disposal, space applications, and fusion energy, as well as to the nuclear science research community. The core elements of the program include: (a) compilation, evaluation, and dissemination of data, (b) priority measurements and standards, and (c) calculations, modeling, and theory. Current evaluation efforts are focused on addressing the data needs in forefront scientific areas. The quality of the tabulated data is assured by a system of evaluations and reviews developed over the years and sanctioned by an international network of nuclear-data evaluators. Online access to the data is provided free of charge by the US Nuclear Data Network; during 1995 there were more than 85,000 online data retrievals from this network.

Future Instrumentation Developments

There are many developments in progress that show great promise for dramatic improvements in accelerator or detector performance. Some examples will be given in this section.

It seems possible to develop a gamma-ray detector array which would have a resolving power about a thousand times that of any array currently existing or planned. Such a detector (called GRETA) would consist of a spherical shell of highly segmented, tapered hexagonal Ge detectors, each of which would be able to locate a scattering point in three dimensions to an accuracy between 1 mm and 1 cm. The gamma ray could then be reconstructed using the energy and position of the interactions. The enormous increase in sensitivity would enable the observation of very rare and exotic decay modes of the nucleus.

A substantial R&D effort will be required to develop a production target for the proposed ISOL facility which can withstand a beam power of the order of 10-100 kilowatts, and still be able to release the radioactive atoms of interest on timescales short compared to their decay half-lives. The technical issues involve the chemistry of the ions produced in the target, thermal and refractory properties of the target material, and shock formation. One novel concept suggested by Argonne National Laboratory is to begin with a beam of deuterons which are then fragmented in an initial target. The resulting neutron beam is then used to produce radioactive isotopes, thus reducing the beam heating problem for the isotope production target.

There are plans to establish a facility for ultra-cold neutron (UCN) work at LANSCE. Phase I would be based on the existing short pulse neutron source at LANSCE. Neutrons with velocity of order 600 m/sec will be Doppler-shifted down to less than 7 m/sec using Bragg reflection from a moving crystal; densities in the range 10-50 neutrons/cm^3 are expected. Phase II would use the full 1 mA (or higher) proton beam available from the linac to produce UCN by down-scattering in solid deuterium. Such a source has the potential to produce UCN densities two orders of magnitude higher than the 80 neutrons/cm^3 currently available at the ILL reactor.

A proposal is being developed to use the new free electron laser facility at Duke University to produce an extremely intense source of polarized gamma rays in the 75 to 185 MeV energy range. Coherent undulator radiation from a single bunch of 1.3 GeV electrons produces polarized laser light in the deep ultra-violet. By filling an appropriately timed second bunch of the storage ring, backscattered polarized γ-rays can be produced with a total intensity of 2×10^9/sec. Using a collimator to eliminate the low energy photons results in a unique photon beam that consists solely of 10^7 photons/sec, all within a 0.5 MeV bin and with a linear polarization of 100%. The source would be uniquely suited for measurements of the nucleon polarizabilities via Compton scattering, and for tests of Chiral Perturbation Theory in pion photoproduction at threshold.

VI. INTERNATIONAL COLLABORATION IN NUCLEAR SCIENCE

Traditionally very strong international collaborations have characterized the nuclear science community. In recent years, as nuclear physics facilities have grown in size and the scientific questions addressed have become more complex, collaborations among the members of this community have increased. Nuclear science researchers often use facilities outside their home institute, and increasingly they choose to work at the most suitable facility available even if it is beyond their national border. This is true both for foreign utilization of the broad spectrum of U.S. nuclear science facilities as well as for the American use of facilities abroad. Specialized facilities featuring unique beams and/or detection systems are often too expensive to duplicate; therefore, the facility best suited for a given study is utilized without regard to its nationality.

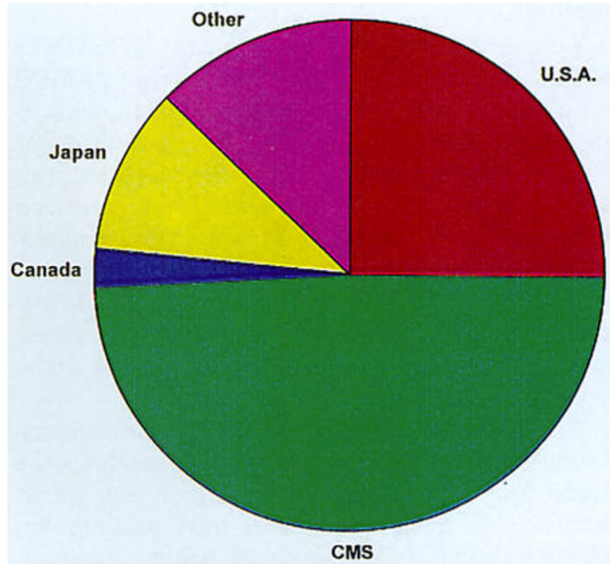

Figure VI.1 Demographics of nuclear scientists active in research. CMS denotes CERN member states. Data from Russia and the other former Soviet states is not included in this figure.

The 1600 scientists involved in nuclear science research in the U.S. represent about 25% of the 6000-7000 researchers active in this field world wide. Most of the remaining nuclear scientists are located in Western Europe and Japan, see Figure VI.1. The per capita concentration of nuclear scientists in Western Europe is about 50% greater than in the U.S. In Canada and Japan it is nearly equal to that of the U.S., and in the rest of the world it is significantly less. Likewise, the approximately 160 Ph.D.'s in nuclear science produced annually in the U.S. are about 25% of the world-wide production.

For the first time international observers from NuPECC (the fourteen nation Nuclear Physics European Collaboration Committee, organized to foster collaboration and planning of future nuclear science facilities within Western Europe) and KAKUDAN (the Steering Committee of the Japanese Society of Nuclear Physics, which coordinates the planning for nuclear physics in Japan) attended the Long Range Plan Working Group Meeting in Pasadena. These observers provided information about future nuclear science facilities and perspectives in their countries. This interaction led to Recommendation 7, which states that close contacts should be maintained with the major nuclear science communities and in particular between NSAC and their advisory bodies. Such discussions, for example, would provide a basis for coordinating the planning for future large nuclear science facilities.

The broad spectrum of nuclear science facilities in the United States described in this plan (see Chapter V) attracts a large international community. The international utilization of the larger U.S. facilities presently is at the level of about 25% with the smaller university facilities having about a 10% foreign involvement. During FY 1994 about 50% of the participants in the programs of the Institute for Nuclear Theory (INT) in Seattle were from outside the U.S. The new American facilities promise to attract even larger international utilization. For example, it is projected that about 30% of the use of CEBAF and HRIBF will be from outside the U.S., and nearly 50% of those preparing to use RHIC are from abroad.

In return during FY1994 about 35% of U.S. nuclear scientists utilized a facility outside of the U.S. Some examples of the foreign facilities available for American use include:

The HERMES experiment at the HERA electron-proton collider at DESY in Germany:

Polarized gas targets will be used in the 30 GeV electron ring to measure deep-inelastic spin-dependent structure functions of the nucleon. The detection system utilizes a large forward dipole magnet to cover the momentum range 5-30 GeV for scattered electrons and produced hadrons.

The Tri-University Meson Facility (TRIUMF) in British Columbia: with the absence of LAMPF as a user facility, the 500 MeV, 200 μA meson-factory at TRIUMF provides U.S. nuclear scientists with convenient access to intense medium-energy beams of pions, muons, and polarized protons. A variety of experiments involving the study of pion and muon interactions with nuclei, of parity violation in the p-p system and of radioactive nuclei produced by these intense proton beams are being carried out by collaborations with significant American participation.

The Paul Scherrer Institute (PSI) in Switzerland: This meson-factory provides particularly large low- and medium-energy pion and muon fluxes. U.S. nuclear scientists have participated in pion absorption experiments using a large acceptance detector system and plan precise studies of pion beta decay.

Special opportunities for heavy-ion physics are provided by three foreign accelerator facilities: the Grand Accélérateur National d'Ions Lourds (GANIL) in France, the Institute of Physical and Chemical Research (RIKEN) in Japan, and the Gesellschaft für Schwerionenforschung (GSI) in Germany. GANIL and RIKEN are intermediate energy facilities used for both radioactive beam physics and nuclear reactions. The long flight path, high resolution, and large solid angle of the SPEG spectrograph at GANIL have been exploited for direct mass measurements. The GSI is an accelerator complex which includes a synchrotron, a separator for radioactive beams, and a storage ring. The high energy (GeV/nucleon range) and the separator-cooler ring complex have U.S. participation in both nuclear structure and reaction mechanism studies.

The European Laboratory for Particle Physics (CERN) in Switzerland, not only provides higher energy relativistic heavy-ion beams than the AGS, but also houses the LEAR facility for low energy anti-protons, which has been used extensively by U.S. physicists. In addition experiments with muons investigating the spin of the proton are ongoing. Likewise the 600 MeV and 1 GeV proton injector beams at CERN have been used for the early development of the Isotope Separator On Line (ISOL) technique for producing beams of radioactive ions. This technique is the basis of the national ISOL facility whose development is given in Recommendation 3.

The principal facility in the world for basic research with neutrons is the 50-MW enriched ^{235}U reactor at the Institut Laue-Langevin (ILL) in France. Although the ILL, like most neutron facilities, is chiefly used for condensed matter studies, important nuclear physics experiments are carried out, e.g. precise measurements of the neutron half-life and correlation coefficients, measurements of beta spectra, a search for the neutron electric-dipole moment, an early neutrino-oscillation search and tests of dynamical symmetries in nuclear structure.

The only dedicated large-scale underground facilities for basic research in nuclear physics are the Laboratori Nazionali del Gran Sasso (LNGS) in Italy and the Baksan Laboratory in Russia. Gran Sasso is host to the Gallex, Borexino and Icarus solar neutrino detectors, to the multi-purpose scintillation detectors, MACRO and LVD, and to double beta decay experiments. At Baksan, the SAGE solar neutrino experiment and a large cosmic ray detector are in operation. Mines in Sudbury, Ontario, and in Japan house the Sudbury Neutrino Observatory (SNO) and the Kamiokande neutrino experiments. All these projects involve significant American participation.

As in the U.S., there is intense interest abroad in the use of accelerated beams of radioactive ions to address a variety of nuclear structure and nuclear astrophysics questions (see Chapters I and IV), which are not accessible with stable beams. Besides the three operational foreign projectile fragmentation radioactive ion beam (RIB) facilities described above (GANIL, RIKEN, and GSI), an ISOL facility also is operational at the Centre de Recherches du Cyclotron of the University Catholique de Louvain in Belgium. This facility is utilized primarily for studies of light heavy-ion reactions applicable to astrophysics. Other ISOL RIB facilities are funded at CERN, GANIL, TRIUMF, the Laboratorio Nazionale del Sud in Italy, and the Institute for Nuclear Studies in Tokyo. A reactor based ISOL facility is also under consideration at the ILL in Grenoble. The choice of accelerators at these planned facilities will provide a variety of RIB species and energies applicable both to nuclear structure and nuclear astrophysics studies. However, none of these facilities abroad will equal the capabilities of the high-intensity multipurpose national ISOL facility under discussion in the U.S. (see Chapter I and Recommendation 3).

Likewise, the need for additional equipment for highly specialized studies often leads to the necessity of funding experimental equipment outside the researcher's home country. For example, major contributions ($19M) have been provided by Armenian, Dutch, Italian, French, Japanese, Russian, and Ukrainian researchers for Hall A and B detectors at CEBAF. For RHIC more than $37M has been obligated to the STAR and PHENIX detector systems by German, Italian, Japanese, Russian, and Swedish researchers, and $20M has been promised by Japanese researchers for spin rotators and Siberian snakes for the RHIC storage ring and for a second muon arm for PHENIX. Sizable contributions also have been made to smaller American facilities, such as the donation of a recoil spectrometer and detectors valued at about $3M to the HRIBF at Oak Ridge National Laboratory by the British nuclear structure community.

Examples of American contributions toward collaborative projects outside the U.S. include $14M for the detector system at the SNO, $2.7M for the NA49 relativistic heavy-ion experiment at CERN, and $1.5M for the HERMES Project at DESY.

There are a variety of other excellent examples of international collaboration in nuclear science. Among these: Recently Australia, Canada, China, India, Japan, and the U.S. have joined the NuPECC countries in converting the previously titled European Nuclear Physics News to the International Nuclear Physics News. Likewise, the U.S. Institute for Nuclear Theory in Seattle and the European Centre for Nuclear Theory (ECT*) in Trento have formalized an agreement in which an advisory board member of each institute will be included as a member of the advisory board of the other institute. This will ensure close communication between American and European nuclear theorists.

The future trend toward more complex specialized experimental facilities and more rapid communications will inevitably foster increased international collaboration. Indeed, the possibility of working and living closely with researchers from other countries is one of the most attractive benefits of our discipline. The increasing multinational collaborations form a coherent international scientific community fostering reliable scientific results, well-developed goals and a cohesive approach toward the future. Such collaborations bring together scientists with very different education and perspectives, which by their very diversity, produce better science.

VII. EDUCATION AND OUTREACH

Education of the next generation of scientists is a very important corollary of fundamental research, and the nuclear science community contributes substantially in this area. A second important corollary is the use of the unique assets of the research enterprise to improve public scientific and technical literacy. In this chapter the current activities and plans of the nuclear science community in both of these critical areas are described.

Graduate Education in Nuclear Science

Nuclear Physics research annually yields more than one-eighth of the nation's Ph.D.'s awarded in physics. The Department of Energy and the National Science Foundation currently support, respectively, 450 and 280 graduate students in nuclear science. The education of graduate students in nuclear science is vital for two general reasons. First, such education is clearly essential for continuing the vitality of our field, as well as for maintaining the overall competence in nuclear science and technology which is so critical for our nation in the modern world. Second, education in nuclear science has proven to be an excellent way to provide technically trained personnel for careers in related fields and for a wide variety of other careers as well.

Graduate study leading to the Ph.D. degree typically involves two years of classroom study and two to four years of original research. Students in nuclear experiment and theory have the opportunity to attack and solve important and challenging problems in science. In most cases, the student is involved in all aspects of his or her project and thus acquires a broad range of skills in addition to the ability to attack a problem in depth. For example, in the course of their thesis work, experimental students typically build and test their own hardware and also become experts on data acquisition and analysis. For theorists and experimentalists, a major part of the training often entails the design and implementation of very complex computer programs.

Graduate training in nuclear science is broadly based, involving techniques and knowledge from different fields, including fields outside nuclear physics. A good example is provided by the recent development of polarized nuclear targets, which involves many diverse technologies, including advanced laser techniques. Much of the graduate student's training is at the technology frontier and is often directly involved with technology transfer. Nuclear science has a long tradition of producing broadly educated and flexible scientists with skills that can be readily applied to the nation's technological needs. It is clear that continued availability of an appropriate technical infrastructure at universities and national laboratories is critical for these educational efforts.

Graduate training in nuclear science very often involves working with a team of scientists from different institutions and different countries. Experiments generally benefit from contributions of detectors or other components supplied by different groups; thus, the successful student also becomes adept at management and communication skills, in addition to acquiring technical knowledge and expertise.

The successful and timely completion of a graduate degree relies on stable planning by the nuclear physics community and on stable funding for the nuclear science program. These conditions require the efficient operation of existing facilities, the timely construction of new facilities and detectors, and support for the technological infrastructure. Significant or unexpected fluctuations in this support can be devastating for graduate education and thereby impede the development of this important human resource.

Subsequent career paths — the history

Nuclear science has been notably successful in attracting high-quality young people into the field. This influx of talent has allowed the field to remain at the intellectual and technical forefront, and to be an important source of technical manpower for many other areas as well. As is the case with other technical fields, many of those who graduate with advanced degrees do not stay in their area of specialization, but rather take

Training America's Talent

Most basic research in the United States takes place in universities — a unique system that serves the function of educating graduate students in a research atmosphere. This feature is what makes U.S. graduate education the envy of the world. Indeed, training the technical talent that industry and government alike depend on is a critical feature of university-based research.

To illustrate how this system has worked in nuclear physics, we have chosen to profile three individuals who studied at the same time over 30 years ago in the same nuclear physics research group. They exemplify the different career paths pursued by well-trained nuclear scientists: Gerald Garvey, a prominent research physicist now serving in the White House science office; Joe Allen, a pioneering NASA astronaut who is now President and CEO of a $140 million company; and Joel Birnbaum, a senior VP at Hewlett Packard who is responsible for this leading computer company's technical strategy and for its $2.5 billion R&D budget. All three earned their Ph.D.s at Yale University in the early 1960s working in the nuclear physics group headed by D. Allan Bromley, who later served as science advisor to President Bush.

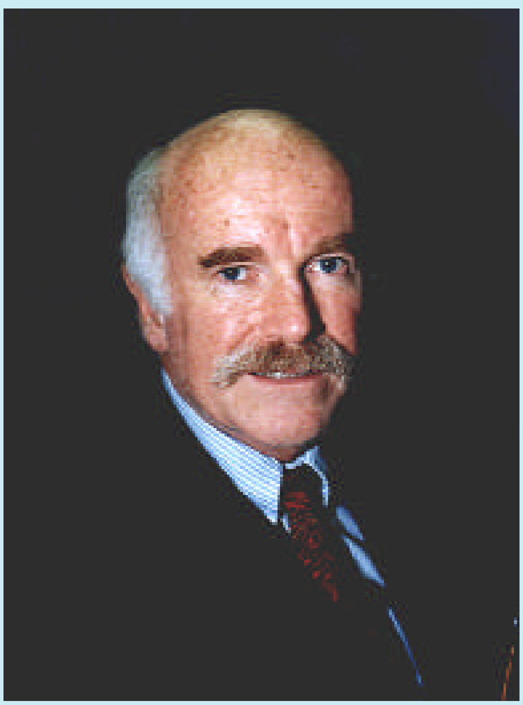

Figure VII.A Gerald Garvey

At that time the Yale group focussed on experimental studies of nuclear structure, initially using a heavy ion accelerator and subsequently building and operating what was then the world's most powerful van de Graaff accelerator. The research of these three students pushed the frontier of nuclear physics — exploring the quantum properties of excited states of carbon nuclei, documenting that some light nuclei have non-spherical shapes, studying the transfer of nucleons between heavy ions. The complexity of the problems and the powerful accelerators and other sophisticated equipment needed to solve them required students to work with other students, technicians, and faculty and to adopt a systems approach. The result was not just a formal education in nuclear physics, but also a breadth of experience that provided both advanced technological skills and the self-confidence to tackle large, unstructured problems.

Of the three students, Gerald Garvey was the most deeply interested in physics and he, indeed, became a research physicist, focused on studies of nuclear structure as a professor at Princeton University. Later he headed the Physics Division at Argonne National Laboratory while holding a joint appointment at the University of Chicago. Garvey subsequently became director of the LAMPF accelerator at Los Alamos National Laboratory, where he studied neutrino interactions and the quark structure of matter. Now, a senior fellow at Los Alamos, Garvey is on leave to serve in Washington, D.C., as assistant director for physical science in the Office of Science and Technology Policy.

Garvey's graduate studies were, in effect, an apprenticeship for his research career. It is a career that has led to original contributions to knowledge in some 150 pub-

Figure VII.B Joe Allen

lished research papers as well as to senior administrative and science policy posts. Garvey himself recalls his graduate studies as intellectually stimulating as well as providing him with a direct springboard into research.

Joe Allen was involved in building some of the earliest high resolution (germanium) gamma ray detectors and also studied the structure of light nuclei. He had been a champion wrestler as an undergraduate and his fellow students recall his positive attitude and cheerful personality. These traits stood Allen in good stead when, after his graduate training and a two-year postdoctoral position at Yale, he applied to the space program and was accepted as the first physicist in the astronaut corps. He flew on two space shuttle missions, devised history's first space salvage operation that recovered two damaged satellites, and served in a variety of positions within the space program, including capsule communicator for the first space shuttle mission. Subsequently, Allen joined Space Industries, Inc., a company providing technology solutions in transportation and other areas to governments, and now heads that firm.

Allen believes his graduate education in nuclear physics "taught a discipline," gave him experience in dealing with tough, intellectually challenging problems, and got him used to putting together state-of-the-art hardware. He found these habits of mind and skills equally applicable to the space program, where he was what he describes as a "technologist", and to the technology-oriented business world he now inhabits.

Joel Birnbaum had been interested in computers as an undergraduate. As a graduate student in nuclear physics, he continued to work summers for IBM as a systems programmer. As part of his thesis, he developed a computer program for analyzing the masses of data generated by Yale's new accelerator. After receiving his graduate degree, he accepted a job with IBM where he moved rapidly into research management, becoming head of computer research and participating in and overseeing the development of the RISC technology that now dominates computer workstations. He left IBM to become head of computer research for Hewlett Packard

Figure VII.C Joel Birnbaum

and subsequently spearheaded that company's move into RISC computing. Birnbaum now directs the entire research laboratory, overseeing corporate R&D activities.

Birnbaum attributes his success in R&D management and technology development in part to several key experiences during his graduate education in nuclear physics. One was the experience of being part of a team, working together to "build things that had to run" — a critical part of industrial R&D. "When you only got time on the heavily-used accelerator every few months", Birnbaum recalls, "you couldn't afford to waste the opportunity because something didn't work." Graduate education in physics also gave him the ability and the desire to achieve a basic understanding of fundamental principles. Indeed, in hiring more than 1000 key R&D staff for HP, he has found that those with an understanding of the underlying science work out best. Finally, Birnbaum says, his education in fundamental science provided him with excellent models, in the person of leading scientists and mathematicians, and trained him how to make technical judgments.

Over the years about 40 percent of the Yale graduate students in nuclear physics have gone into industry, 40 percent into university research, and 20 percent into government — a pattern illustrated by the diverse careers of the three students profiled here. This is a story which could be told many times over, with slight variations, by examining the careers of those emerging from various nuclear physics groups at various universities. As those careers suggest, highly trained talent may be one of the most important results of university-based fundamental research. What is also evident is the broad utility of the discipline of problem-solving at the frontiers of knowledge and of training in nuclear physics, even for pursuits such as setting national science policy, operating in space, running a hightech business, or developing competitive computer systems.

One of Today's Graduate Students

The continuing ability of nuclear science to attract and train outstanding young people can be seen in the career paths and experiences of students such as Todd Peterson, currently a graduate student working with 'postdoc' Angie Betker and Professor Steve Vigdor at Indiana University. Todd was an undergraduate at Gustavus Adolphus College, a small liberal arts college in St. Peter, Minnesota. Despite often excellent physics programs, opportunities for involvement in research can be scarce at small schools. In 1990, Todd applied for and was accepted into the Indiana University Cyclotron Facility (IUCF) Research Experience for Undergraduates (REU) program, sponsored by the NSF. Working side-by-side with nuclear physicists and medical technicians, Todd was involved in the initial feasibility studies for a proton radiation therapy program at the cyclotron facility. He designed and built a secondary-electron emission monitor (SEM), a crucial ingredient to ensure proper dose administration, and was later part of the team which measured the energy loss suffered by 200 MeV helium-3 (^{3}He) nuclei penetrating biological tissue. Heavy nuclei, such as ^{3}He, stop in a well defined range of material, giving them a distinct advantage over x-rays and electrons in radiation treatment. He also helped develop the double-scattering foil system that is used to produce a beam of the proper transverse dimensions.

Following his REU work, Todd received a Rhodes Scholarship, and in 1993 obtained a B.A. in Physics and Philosophy from Balliol College, Oxford. He then decided to return to IUCF; but rather than continue his applied work in medical physics, Todd began to focus his attention on some of the more fundamental questions facing nuclear physics. One idea that attracted him was a program just getting underway to search for the as yet unobserved 'pionium' molecule. This object, consisting of oppositely charged pi-mesons (π^+ and π^-) co-orbiting as an atomic bound state, would be the lightest possible strongly interacting system, and as such would provide important constraints on models of strong interactions at very low energy. Todd joined the effort to form this molecule at the IUCF Cooler ring using the reaction $p + d \rightarrow {}^3He + \pi^+ \pi^-$. It was clear that although detection of a ^{3}He would be a necessary condition for each potential pionium event, it would certainly not be sufficient. Todd therefore designed a set of counters to detect any free pions present in coincidence with the forward-going ^{3}He. Detailed analysis has since shown that this approach significantly reduced backgrounds, but that the production cross sections may also be smaller than anticipated. At the moment, plans for more efficient detection schemes or alternative production reactions are under consideration; but for the students involved in these programs, such as Todd, these challenges are opportunities to develop the physical intuition and technical skills they will need to succeed throughout their careers, whether in academia or in industry.

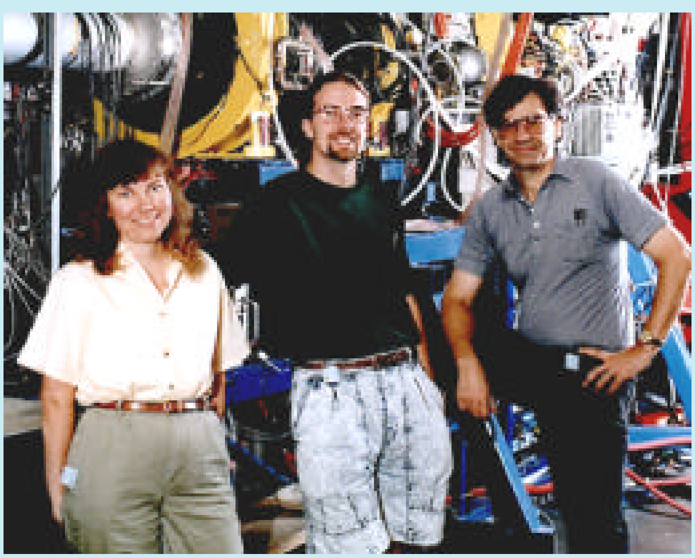

Figure VII.D Angie Betker, Todd Peterson and Professor Steve Vigdor standing in front of the apparatus used in their experiment.

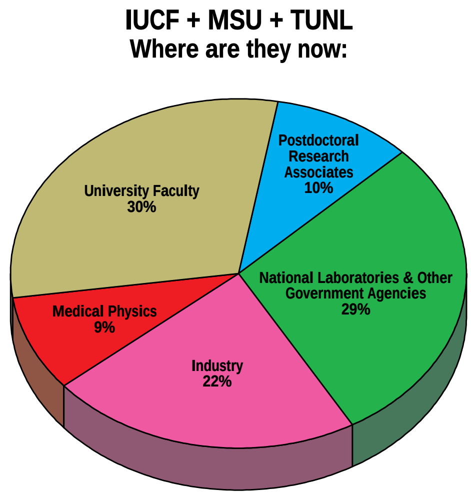

Figure VII.1: Summary of where nuclear physics PhDs from three large institutions (Indiana, Michigan State and Triangle Universities) are currently employed.

positions in other technical and related fields. Later in their careers many of these individuals move into even more diverse areas.

In an attempt to answer more quantitatively the question of where scientists trained in nuclear science end up working, we canvassed the records of three university-based nuclear physics accelerator laboratories. These laboratories are the Indiana University Cyclotron Facility, the National Superconducting Cyclotron Laboratory at Michigan State University, and the Triangle Universities Nuclear Laboratory operated by Duke University, North Carolina State University, and the University of North Carolina. Each facility has maintained fairly complete records of the positions taken by Ph.D. graduates who performed their doctoral research at the accelerator laboratory. In many cases these records include career changes which occurred after the initial position following completion of the degree. The results of this canvas are shown in Figure VII.1. The postdoctoral research associate positions are held in general by young people who will move to more permanent positions within a few years. It is seen that the permanent positions are roughly evenly divided between Universities, National Laboratories and other Governmental Agencies, and Industry. The field of Medical Physics has long been a special and important application of nuclear science and is displayed separately for this reason; most of these positions are industrial.

It is notable that all the categories of permanent positions shown in Fig. VII.1 display career opportunities whose scope is much broader than that of nuclear science. We believe that the variety of careers undertaken by those trained in nuclear science at these three facilities is typical for those trained in the field in general. Records also show that this variety is not a recent phenomenon but rather has been characteristic of graduates in nuclear science for decades.

Assessment of current career prospects for young people trained in nuclear science

Career prospects for young scientists is a subject of considerable current interest both within the scientific community and beyond. The nation rightfully wishes to know if we are using the talents of our young people appropriately and if we are recovering the investment in science graduate education. It is clearly very important that young people receive a realistic assessment of career opportunities before deciding to devote their considerable time and energies to graduate study in a particular field. In the process of preparing this Long Range Plan we have addressed these issues directly.

Available statistics indicate that employment opportunities of nuclear physics Ph.D.'s within our own field have been relatively constant over at least the past decade. However, the end of the Cold War and the decrease in funding both for basic research and for the support of long term research in industry have eroded a major sector of the traditional base of job opportunities for Ph.D. physicists in all fields. The average time spent from the start of a Ph.D. program to finding permanent employment has increased over the last decade. In particular, the most recent graduates appear to be spending a longer time finding initial employment and more time in temporary or postdoctoral positions.

Although many Ph.D. nuclear physicists remain in academic positions, most enter the work force in a diverse range of activities. While any unemployment or underemployment is cause for concern, the rate for each appears to remain relatively low for physics, including nuclear physics. For example, recent surveys of Ph.D.'s trained in physics show consistently that unemployment is around the 2% level and underemployment around 6%, as reported by the individuals themselves.

Members of the nuclear science community are strengthening efforts to expose graduate students to the full range of career opportunities and to make certain that they understand at all stages of their training the prospects for employment both within nuclear science and in other fields. We strongly support these important activities.

Undergraduate Education

An undergraduate degree in physics provides an excellent preparation for the many different career paths that the graduates may follow. Many universities indeed have programs which prepare physics majors for the changing demands of the work place. For example, many tracks for physics majors exist which focus on preparation for secondary education, business, laboratory instrumentation, interdisciplinary programs in chemistry, biology, medicine and in environmental and public policy.

The nuclear science community has sought to improve the quality and breadth of the undergraduate physics major education by providing experience in active research laboratories. Many have been supported by the very popular NSF Research Experiences for Undergraduates (REU) Program. This program has two parts, the REU Site Program and direct supplement grants awarded to individual NSF-supported principal investigators. While the program supports research activities for undergraduate students in all fields of physics, many students work with nuclear physicists. The NSF supported 33 sites last year and will support 40 sites this year through the Special Program Office. Sites that are predominantly nuclear physics oriented are located at Florida State, Indiana, Michigan State, the University of Virginia, and, starting this year, at the University of Washington. The Research at Undergraduate Institutions (RUI) has made it possible for physics faculty members at undergraduate institutions to involve their students in research.

Similarly, the DOE supports many educational undergraduate activities. For example, the Science and Engineering Research Semester and the Undergraduate Student Research Participation program involve students in nuclear science projects. The Division of Nuclear Chemistry and Technology, in partnership with DOE, has developed an intensive six-week summer school program designed to encourage undergraduate students to pursue careers in nuclear science. This program, consisting of both lectures and laboratory work, exposes students to nuclear scientists working in areas of national interest, from nuclear power and waste disposal, to nuclear non-proliferation, radiation safety, and nuclear medicine.

While these specific NSF and DOE programs are important especially in providing opportunities for students who would otherwise not be able to participate in research, it should be understood that many more undergraduates are involved in nuclear physics research through the usual research grants for faculty. At a large number of universities nuclear physics faculty involve undergraduates in their research projects, including senior theses and part-time and summer jobs. These undergraduates are members of the research team and obtain invaluable experience for their future educational and career pursuits. The synergism between research and teaching improves the quality of the undergraduate experience. Concurrently, the fresh ideas from the younger members of the research teams enhance the vitality of the field.

Earlier Education, Outreach, Scientific Literacy

The rapid pace of technological advances in the world today demands the support of a scientifically and technically literate public. Yet the future of the country and its economic welfare depend increasingly on the level of the technical and scientific sophistication of the population. Scientists recognize this issue as a serious national problem and recognize that they have significant responsibility and an important role to play in strengthening instruction in the particularly critical fields of mathematics, science and technology and in enhancing the scientific awareness of the public. The nuclear science community, supported by DOE and NSF, is committed to the following goals:

- increasing the awareness of the public in scientific matters,
- improving the basic science education of grade and high school students,
- strengthening the background of K-12 teachers,

Broadening the Talent Base

New partnerships between research scientists at universities and science teachers at local high schools have developed which stimulate sharing the excitement of new scientific discoveries with school teachers and their students, especially students who previously may not have had such opportunities. One particularly innovative program has been implemented under the auspices of the National Science Foundation. Interested students at Lincoln High School in Los Angeles, which has a predominantly Latino population, enroll in a mathematics/science university preparatory program (UPP) co-directed by Prof. Martin Epstein, who is a member of the nuclear physics faculty at California State University, Los Angeles (CSULA). The goal of the program, which began in 1989, is to graduate a significant number of these students from CSULA with degrees in mathematics or science related areas. At present 312 high school students and 58 college students are enrolled in UPP. Teachers and parents are actively involved in these activities. The high school students are given after-school tutoring, participate in Saturday programs on campus and go on field trips to laboratories engaged in research and development.

The overall commitment of the participants is evident in the fact that, at the present time, four of the UPP students at CSULA are working on nuclear physics experiments being carried out at MIT/Bates and at a laboratory in Mainz, Germany. Furthermore, for the last 5 years the UPP high school physics teacher, Mr. David Swanston, has also been working with this research group. Long range sustained combined efforts of active researchers and science teachers create an environment in which youngsters can learn to appreciate and contribute to science, and further can carry their excitement to their homes and communities.

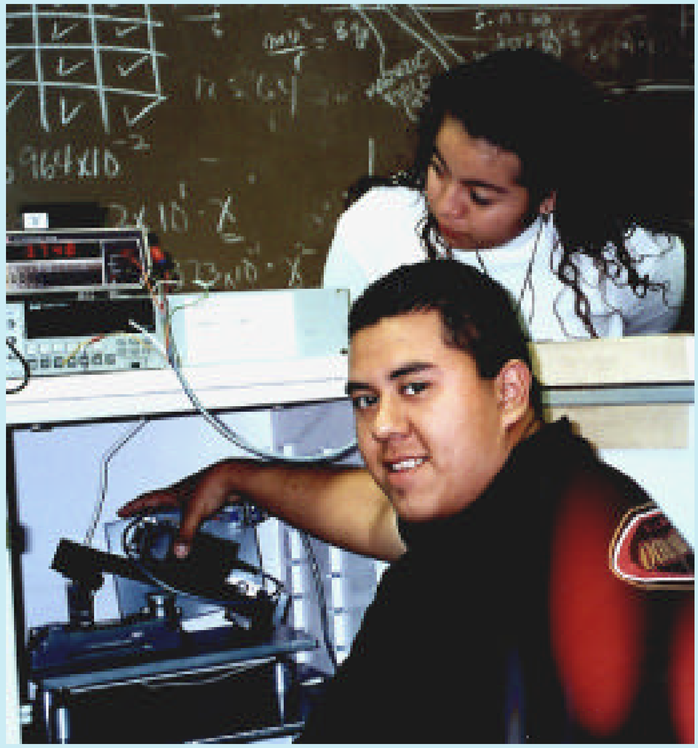

Figure VII.E Students from Lincoln High School in Los Angeles examine the apparatus used in the experiment in which they participate.

Outreach to community and schools

In spite of the fact that we are surrounded by technology, from computers to videos to virtual reality, the public often shows only a passing interest in the science that underlies this critical aspect of our society. The lack of appreciation and understanding of science at even a descriptive level is of great concern to educators, parents, government leaders and the scientific community. U.S. universities and national laboratories are playing an increasing role in addressing these issues. A large fraction of CEBAF's outreach activities address science education in local schools. The BEAMS (Becoming Enthusiastic about Math and Science) project brings the excitement of the laboratory to middle school students through hands-on activities. The coupling of research to teaching enhances the quality of science education and the public awareness of science.

Figure VII.F Middle school students learn how scientists at CEBAF study microscopic objects that can't be seen directly. The shape and orientation of an object can be inferred in this experiment, as in the actual scattering experiment with an electron beam, through indirect observations. Selected objects with quite distinct structures — triangles, circles, squares — are hidden beneath an inverted pie pan. Their shape, like that of nuclei, can be established through observations of the scattering of a probe projectile from the hidden object.

Figure VII.G Open house visitors at CEBAF using lightpipes and scintillators in a presentation designed to describe the detectors used to observe the high energy particles resulting from interactions between electron beams and nuclear targets.

- enriching the educational experience of undergraduate science majors,
- attracting underrepresented minority and women students to science.

The sections below describe the efforts of the nuclear science community in addressing these goals. Information was obtained from a survey of members of the American Physical Society Division of Nuclear Physics, the national laboratories supported by the DOE and NSF, and from contacts with the American Chemical Society Division of Nuclear Chemistry and Technology. The survey focused on three questions regarding undergraduate education, outreach and scientific literacy. What is evident from the responses to the survey is that there are many members in the field who are committing increasing amounts of their time and energy to these problems. Their efforts represent a commitment to important national goals.

Elementary and middle schools: K-8

Young children are fascinated by science; it is essential to capture this fascination and make a positive impact on the attitudes of students at an early stage of their education and on the teachers who provide primary education. Nuclear physics faculty members at colleges and universities, and scientists at national laboratories have made, and continue to make, significant efforts to reach children in elementary and middle schools and to impart to them the excitement of science. Successful programs have benefited from a close interaction of university and education faculty members with local school teachers. Other initiatives have been mainly steered by students, such as undergraduates from the Society of Physics Students or graduate students. The colorful names of some of these programs reveal the extent and creative span of these outreach activities: the Physics Petting Zoo, the Flying Circus of Physics, Science Theater, Saturday Morning Physics exploring the Frontiers of Modern Science. A broad variety of existing programs which exploit different approaches has been used to expose youngsters to scientific ideas:

- Show and tell programs. Some mobile laboratories, designed for students to explore directly by hands-on experience, travel to schools and have reached thousands of students per year. Development of displays for children's museums.
- Visiting Minority Professorships have been established at research universities. The recipients of these professorships interact frequently with students in inner-city schools.
- BEAMS at CEBAF: this program brings the excitement of science to grade school students. In partnership with the local schools and the Commonwealth of Virginia, entire classes are brought to the facility for a full week of immersion in the scientific environment. To date about 30,000 students have benefited from BEAMS and other programs at CEBAF.

The continuation and expansion of these programs are critical to the nurturing of the natural curiosity of our young people and to the development of their scientific and technological sophistication.

High schools: teachers and students

The alienation of young people from science and mathematics is a very serious concern for our nation. The problem arises because students often perceive these subjects as formidable and as being unpopular with their peers. Nuclear scientists are working to improve both the way science is viewed by young people and the quality of science education by establishing working partnerships with science teachers. Nuclear physics laboratories and universities organize programs for high school students and, often, their teachers as well. These have been well attended and frequently oversubscribed. Hundreds of students have participated in these activities. Some of these efforts have been supported by federal funds or by the local institution; however, many rely on the voluntary work of individual scientists.

The examples below illustrate the variety of approaches that have been used.

- Saturday classes for in-service teachers. Multi-week summer programs for students which sometimes include teachers as well. Long term university based programs that nurture the students from middle or high school through college graduation.
- Lectures and demonstrations in schools. Development of instructional material for schools. Extension of the computer facilities to high schools, so that students and their

teachers can access the information superhighway and the many innovative activities that are available such as videos, or "virtual tours through a laboratory".

- Career shadowing programs where the middle and high school students can spend a day following an active researcher in the laboratory.

Partnerships between universities and high schools provide a constructive approach to enhance the science programs in high schools.

Activities addressing under representation of women and minorities

For a number of complex societal reasons, large segments of our society are underrepresented in science and technology. Most scientists are acutely aware of this imbalance. The nuclear community has endeavored to encourage women and minority students to pursue careers in physics through individual volunteer efforts and specific programs supported by the DOE and NSF. Many of the programs addressing the K-12 students are very proactive in involving women and minorities. For example, it has long been realized that middle school is a critical time in the educational development of young people. Many universities, colleges and national laboratories sponsor workshops which bring women and minority students in middle schools for a day or more to participate in hands-on science (especially physics) and to meet practicing scientists.

National and university laboratories have also committed resources to recruit students from Historically Black Colleges and Universities (HBCU's) and Hispanic Serving Institutions (HSI's) to participate in the laboratories' summer science research programs. These programs sometimes include support for HBCU faculty participation. For example, CEBAF's efforts have contributed to a significant growth in faculty hirings in HBCU's and HSI's. As a result, Hampton University has developed a new Ph.D. program and graduated about 20 undergraduates, all African American, one third of whom have done research in nuclear science. Mentoring programs for promising minority undergraduate have been instituted by CEBAF and various universities.

Programs initiated over the past several years, as well as laudable efforts at several leading research universities and laboratories, attempt to address the paucity of women and minorities in the field. Nuclear Scientists have been very active in these programs, such as the American Physical Society Women in Physics project. However, there is still a severe underrepresentation of women and minorities in physics and the community must continue its efforts to correct this situation.

Several possible directions which would prove beneficial have been identified. It is necessary to strengthen the research infrastructure at HCBU's. This action would significantly improve the full participation of their students in mainstream research. Additional Federal support could be directed towards research universities which have strategies to increase both *the number and graduation rate* of women and minorities. Finally, it is important that efforts continue to be made to increase the number of women and minority faculty.

Scientific literacy: outreach to the public-at-large

The issues of education, outreach and science literacy are critical to the future of the nation and of science.

Nuclear scientists have had a long tradition of public service and have engaged in diverse outreach activities which have reached a wide audience. Some of the most successful endeavors have involved

- Open houses (some have attracted as many as 7000 visitors) at laboratories of all sizes and popular lectures to civic groups.

- Development of exhibits in nuclear physics for museums; publications explaining and popularizing science, in particular the contributions made by nuclear scientists; TV Programs on PBS or cable channels.

In addition, the Division of Nuclear Physics of the American Physical Society has established a Committee on Education whose charge is to lend support to existing programs, and develop new initiatives including outreach and mass media dissemination of scientific accomplishments. An essential feature of this committee's work consists of publicizing within the community the efforts that individual members of the community are making on behalf of outreach and scientific literacy.

Conclusions

Based on the reports obtained from government agencies, professional societies, the national nuclear physics laboratories, and from individual nuclear scientists, the following actions are recommended to enhance outreach programs, to increase women and minority representation in science and to broaden the educational environment of physics students:

- Continue the support of effective programs for recruiting, training and retention of underrepresented groups.
- Support outreach programs in the context of sustained, long-range efforts.
- Encourage the funding agencies to continue to capitalize on the direct educational benefits of their primary research missions. Federal dollars spent in basic research at universities have a major impact on the quality and depth of undergraduate science education.

VIII. INTERDISCIPLINARY AND SOCIETAL APPLICATIONS

Introduction

Nuclear science continues to have a major impact in other areas of science, in technology, medicine, and national security. Often a development in a sub-discipline of nuclear research leads to new insight and capabilities in a seemingly unrelated field. Clearly these applications depend upon parallel developments in other sciences and engineering, reflecting the complex network of interrelations which determines the rate of progress in the modern world of science and technology. The collection, evaluation and on-line dissemination of nuclear data provided by the nuclear physics community for both applied and basic research purposes is discussed in Chapter V.

Nuclear science techniques are especially important in medicine. Computerized axial tomography (CAT), nuclear magnetic resonance imaging (MRI), and positron emission tomography (PET) are important non-invasive imaging techniques which provide high resolution, three dimensional images of the interior of the human body. Accelerators and radioactive sources are widely used for cancer radiation therapy with photons and electrons, and alternative treatments with neutrons and energetic beams of protons or light ions are being developed by teams of medical and nuclear scientists. Radioactive isotopes produced by accelerators or nuclear reactors are widely used in medical treatments and diagnostics, and in biomedical research.

Nuclear methods are widely used in materials research and advanced materials manufacturing. Examples include non-destructive testing via computerized tomography or neutron radiography, the ubiquitous use of ion implantation by the semiconductor industry to produce densely packed microchips, sterilization of heat sensitive materials by X-ray, gamma (γ)-ray, or electron irradiation, detailed analyses of impurities in surface layers via Rutherford backscattering, non-destructive wear analyses, the production of microscopic pore size filters by heavy ion irradiation of plastic foils, and the production of pinned vortices in high-temperature superconductors by irradiation with energetic ions.

Nuclear science contributes to the exploration of space by providing detector technology and calibrations for instruments used on space flights, by providing beams needed to develop radiation hardened electronic components and to assess health risks to astronauts from cosmic radiation during extended space missions.

Proton-induced X-ray and γ-ray emission techniques (PIXE and PIGE) and, with growing importance, the ultra sensitive technique of accelerator mass spectrometry (AMS) provide important data needed for the understanding of climatic change, global air and water circulation patterns, and stratospheric ozone depletion, and for the monitoring of air and water quality. These techniques have become indispensable tools for archeology, as well as for the authentication of rare artifacts. Neutron interrogation techniques are routinely used to monitor the chemical composition of coal at mines, coal preparation plants, and utilities in order to determine its sulfur, water, ash, and energy content. Nuclear technology is indispensable for monitoring existing radioactive waste repositories.

There are broad applications in the areas of safety and national security. The common smoke detector uses a small radioactive source to measure changes in the ionization of air which occur during combustion. Nuclear scientists have developed an inexpensive method to measure the amount of radon in homes (radon is a naturally occurring radioactive gas which emanates from the ground and which can accumulate in poorly ventilated building enclosures). X-ray and neutron scanning techniques allow the detection of weapons and contraband at airports or other sensitive locations, and neutron interrogation techniques allow the discrimination between biological and chemical weapons without need for opening the warhead or the container in which the warhead is stored.

Nuclear science, of course, continues to have a profound impact on the production of energy, including the exploration and utilization of the world's oil reserves. Nuclear fission reactors currently provide about 19% of the nation's electricity and about 25% of the world's electricity. Without nuclear energy, more CO_2 and other pollutants would be released to the atmosphere. Perhaps most importantly for the future, nuclear science continues to make important contributions to solve the problem of controlled nuclear fusion which has the potential in the long term to become an almost inexhaustible and clean energy source.

This chapter highlights the important aspect of interdisciplinary and societal applications of nuclear science with an eye on both the past and the future. By necessity, one cannot do justice to the whole range of applications in the short space available, and omission of even important examples is unavoidable. We focus on examples of direct relevance to societal goals – some examples chosen are now major successes of applied nuclear technology, others are still in the early stage of development, but have a good chance to be important in the future. Of comparable importance as these tangible applications is the education of young scientists trained in the high-tech nuclear science laboratory environment where teamwork and the convergence of many different skills are prerequisites for progress. These educational and other interdisciplinary aspects of nuclear science such as nuclear astrophysics or tests of fundamental symmetries, are discussed in other chapters of this report.

Medical Applications

Technologies emerging from nuclear research have a continuing important impact on medicine. Today, the field of "nuclear medicine" comprises 3500 hospital-based nuclear medicine departments. In the U.S., nuclear diagnostic medicine generates approximately $10 billion/year in business. Radiation therapy using linear electron accelerators generates business of about $18 billion/year while nuclear medicine instrumentation is a market of about $3 billion/year. While a large business, more importantly, these activities measurably improve the health of our citizenry.

Cancer Radiation-Therapy

Cancer accounts for approximately 25% of all deaths in the United States and a million new patients develop serious forms of cancer every year. Approximately half of these patients are treated with some form of radiation therapy.

The most common form of radiation treatment is photon therapy, often complemented by direct irradiation with electrons. Treatment with other forms of radiation (neutrons, protons, and heavy ions) has been pursued at a few institutions throughout the world, largely by making use of aging accelerators initially constructed for research. Therefore, broad clinical experience is still lacking for many promising treatment options. Only in recent years have accelerators been tailored to meet optimally the needs of hospital-based treatment facilities, and it is likely that significantly improved radiation treatments will come into existence during the next decade.

Nuclear scientists are presently developing new and more reliable calculations of dose deposition by neutron or charged-particle beams which also take into account the effects of nuclear interactions between the beam particles and the traversed tissue. Many of the needed cross sections are not known and have to be calculated from reaction models. These model calculations will have to be tested against benchmark nuclear physics experiments.

Photon Therapy

Irradiation of cancers by energetic photons generated by compact electron accelerators is now an integral part of cancer treatment protocols. The dose delivered to the patient in one irradiation reaches a maximum near the point of entry into the body and then decreases exponentially with distance through the body. Direct irradiation with electrons, often used to supplement photon treatments, gives rise to a similar dose distribution. Thus, for a single exposure, healthy tissue unavoidably receives a higher dose than the cancer. The damage to healthy tissue can be ameliorated by irradiating the tumor from many different directions, all intersecting at the site of the tumor.

Teams of radiologists, physicists and computer programmers work together to optimize and fine-tune three-dimensional treatment plans (conformal therapy) which maximize dose-deposition in the tumor while minimizing exposure of healthy tissue. The software packages used for these purposes are often derived from simulation programs written for basic nuclear and particle physics research.

Even better dose localization is possible, in principle, by using heavy ionizing particles such

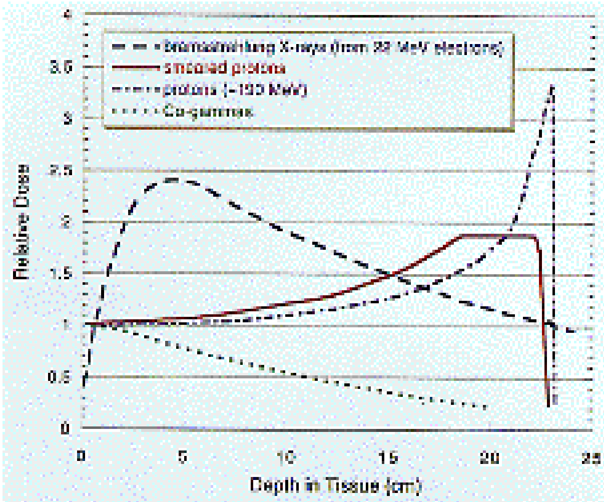

Figure VIII.1: Relative dose at various depths in tissue for bremsstrahlung X-rays generated by 22 MeV electrons (dashed curve), for 190 MeV protons (dot-dashed curve), for protons with smeared energy distribution to provide a plateau dose profile (solid curve), and from γ-rays produced by a cobalt 60 source (dotted curve).

as protons or heavy ions. However, such treatments require more expensive accelerators – and much additional clinical research.

Proton Therapy

Protons can be delivered with high accuracy such that they are stopped precisely in the tumorous tissue, see Figure VIII.1. Since the energy deposition is at its maximum close to the end of the proton's range, damage to healthy tissue in front of the tumor is reduced and there is no damage behind the tumor. Thus major improvements can be expected from proton radiation therapy. For tumors deep in the body, the accuracy of dose delivery by protons (and even more so by heavy ions) can be limited by the accuracy with which the tumor's shape and location are determined. Advances in imaging and localization techniques could thus lead to further improvements in radiation therapy.

At present (1995), over 16,000 patients have been treated with protons delivered, to a large extent, by accelerators built for physics research. Proton therapy is now a widely accepted treatment for cancers near the eye or near the spinal cord as well as for deadly blood clots deep inside the brain which are known as arteriovenous malformations (AVMs). The first dedicated proton therapy accelerator for use at a major hospital facility has been designed by accelerator physicists from Fermilab. The facility was commissioned in 1990 at Loma Linda Hospital near Los Angeles and is presently treating about 50 patients per day. A second dedicated facility is being planned for Massachusetts General Hospital. In addition, a new cancer-treatment research program has been started at the Indiana University Cyclotron Facility. Clinical research at these and other facilities in the world should provide a firm basis for evaluating cost versus benefit of proton therapy as compared to the less expensive photon therapy.

Neutron Therapy

Neutrons were the first heavy particles to become available for therapeutic applications. Neutrons produce a high linear energy transfer (LET), i.e., the density of broken chemical bonds in the cell is high. High LET radiation has the advantage of overcoming a cancer cell's resistance to radiation damage more effectively than low-LET radiation, such as photons, electrons or protons. Cancer cells are often low in oxygen content, which makes the DNA repair mechanism more effective than for normal, more oxygen-rich cells. As a consequence, cancer cells in oxygen depleted tissue are more resistant, by up to a factor of three, to low-LET radiation than normally oxygenated cells. For high-LET radiation, this enhanced resistance is reduced to a few tens of percent. In this type of tissue, neutrons should be biologically more effective in killing cancer cells than the more frequently used and more economically produced X-rays or electrons.

After three decades of clinical experience, it has been estimated that some 10-15% of patients referred to radiotherapy would benefit from neutron therapy, for cancers such as salivary gland tumors, some head and neck tumors, advanced tumors of the prostate, and melanomas. Beginning in the 1980's, a new generation of facilities were constructed that incorporate high energy cyclotrons and neutron treatment gantries with improved beam definition and penetration. A recent example is the superconducting neutron-therapy cyclotron designed and constructed by the National Superconducting Cyclotron Laboratory at Michigan State University. The neutrons are generated by a 50 MeV deuteron beam which impinges on an internal production target. The cyclotron and an adjustable neutron collimator are mounted on a gantry that rotates around the patient to allow treatment from many

Improved Cancer Treatments

Over one million Americans develop serious forms of cancer every year, and about half of these patients are treated with radiation. As new forms of radiation therapy and new accelerators designed explicitly for cancer treatment come into wider usage over the next decade, it is likely that there will significant improvements in radiation treatment — hopefully resulting in more cures and fewer side effects. These advances will make use of techniques, knowledge, and in some cases accelerators stemming from nuclear physics.

Most of today's radiation treatments use x-rays or gamma rays. These forms of radiation are high energy photons, which deposit most of their energy where they enter the body, and they usually continue to deposit energy after passing through a cancerous tumor until they leave the body. That means healthy tissues sometimes receive higher doses of radiation than the tumor. But now new types of radiation therapy developed by nuclear physicists and radiologists to solve this problem are beginning to come into medical use.

One of these new treatments is known as proton therapy. Protons deposit most of their energy where they come to a stop, not where they enter the body. How far they penetrate can be precisely controlled so that they come to a stop and deliver their radiation within the tumor. Compared to x-rays, this allows radiologists to increase the radiation dose to the tumor while reducing the dose to healthy tissues.

The radiation from either x-rays or protons can be focused more tightly on the tumor by using multiple beams that intersect at the site of the tumor. Even with four beams, however, x-rays still deposit a sub-

Figure VIII.A A medical technician aligns a patient in a superconducting cyclotron facility at Harper Hospital in Detroit. The compact cyclotron is being used for neutron irradiation of cancer and is based on the technology developed for research cyclotrons built at Michigan State University. Both the cyclotron and collimator for the neutron beam are positioned on the right about 45 degrees above the horizontal and can be moved to be at any angle relative to the patient.

stantial amount of radiation in healthy tissue, while with only three proton beams, virtually all radiation is confined to the tumor itself.

More than 16,000 patients have been treated with protons, mostly at accelerators originally built for physics research. Now physicists are designing accelerators specifically for cancer therapy, such as one which has been in operation since 1990 at Loma Linda Hospital near Los Angeles and one under construction at the Massachusetts General Hospital in Boston. Research is continuing with other new forms of radiation therapy using neutrons and heavy ions. Neutrons appear to be more biologically effective in killing cancers than many other forms of radiation, especially in oxygen-poor cells such as prostate tumors, some head and neck tumors, and the most dangerous form of skin cancer, melanoma. Implanting boron-containing compounds in the tumor appears to have promise as a way to enhance this effectiveness even further, because boron nuclei readily capture neutrons, thus localizing the dose within the tumor. Heavy ions appear to have similar advantages to those of neutrons, but can potentially be focused even more tightly on the cancerous tissue.

One drawback to these new therapies is that they are more expensive than traditional x-ray treatments. More clinical research is needed to see whether the benefits of more effective and more carefully-localized radiation treatments are worth the higher costs. Nonetheless, the potential for significantly reducing the side effects from radiation treatments while curing more patients of their cancers is a strong reason to continue the research.

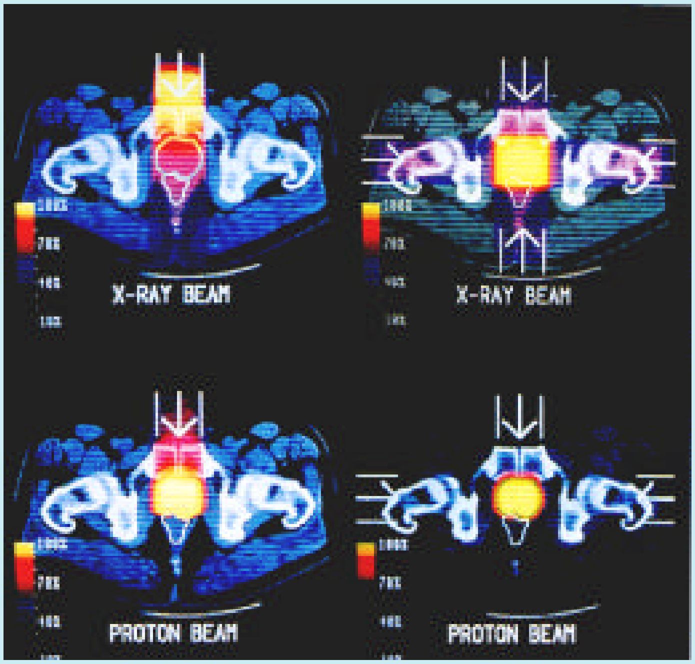

Figure VIII.B A cancer treatment has been developed which uses proton beams from accelerators similar to the ones developed for nuclear physics research. The conventional treatment for cancer involves X-rays which deposit more of their energy where they enter the body and then less as they travel through the body to a tumor; thus normal tissue gets a higher dose than the tumor. Protons penetrate tissue to a controllable depth and deposit most of their energy at the end of their range; thus more of the damage is done to the tumor. The four images compare X-ray beams and proton beams in their ability to localize dosage. A tumor of the prostate gland is shown in the middle of each image. The colors indicate how the energy is deposited in the tissue — yellow is maximum, followed by red, orange and purple. The figure is from Loma Linda University.

directions and thus minimize radiation damage to the healthy tissue surrounding the tumor (see Fig. VIII.A). This cyclotron is in operation at Detroit's Harper Hospital where neutron therapy is now an integral part of a variety of new cancer treatment protocols which already show highly promising results for tumors that are otherwise difficult to treat.

Boron Neutron Capture Therapy (BNCT)

Boron nuclei have a large probability for neutron capture and subsequent splitting into two charged fragments which have a short range in tissue. Selective implantation of boron into a tumor thus offers a near-ideal dose deposition. First trial treatments of brain tumors in the early 50's failed, firstly because of the unavailability of drugs which could deliver boron nuclei selectively to cancer cells and, secondly, because the early tests used thermal neutrons which deliver a large dose to the surrounding brain tissue. This situation has recently been turned around by the development of a new boron compound which shows a specificity for tumor tissue of roughly 5:1 over normal tissue. Additional advantages are expected from the use of epithermal, more penetrating neutrons which reduce exposure of the surrounding tissue. New trial treatments at the Brookhaven National Laboratory Medical Research Reactor have been recently approved by the FDA. If successful, nuclear accelerator technology could be used to develop relatively inexpensive neutron generators to augment reactors and Californium-252 sources.

Heavy-Ion Therapy

Beams of light nuclei (such as carbon or neon) with energies of 400 - 800 MeV per nucleon are nearly ideal dose delivery vehicles for cancer radiation therapy. Similar to neutrons, these ions produce high LETs which may offer the advantage of selectively destroying cancer cells (as compared to normal cells). In addition, they have an even more sharply defined dose delivery profile than protons. However, the required heavy-ion accelerators are very expensive. Initial studies with light-ion beams such as carbon or neon were conducted at the former Bevalac accelerator at Berkeley, but these limited studies were insufficient to establish a clear clinical advantage over proton therapy. Further clinical research is needed to assess the effectiveness of heavy-ion radiation therapy. Research with such beams is now being pursued at the $400 million dedicated light-ion clinical facility in Chiba, Japan, and (starting in 1997) at the GSI laboratory in Germany. American medical and nuclear scientists will follow closely the results of these clinical trials.

Diagnostic Imaging

Advanced nuclear diagnostic techniques such as computerized axial tomography (CAT), nuclear magnetic resonance imaging (MRI), single photon emission computerized tomography (SPECT), and positron emission tomography (PET), have revolutionized medicine by providing ways to "see" inside the body without surgery. CAT scans, MRI and, increasingly, SPECT are now standard diagnostic tools of comparable importance to basic X-rays, and the needed instruments can be obtained from commercial manufacturers. The practitioners of advanced PET techniques are often nuclear physicists who continue to develop increasingly powerful instruments and work with physicians to apply the techniques in the medical environment.

Single Photon Emission Computerized Tomography

The SPECT imaging technique uses drugs containing small amounts of short-lived radioactive isotopes. The most important radioisotopes used in over 90% of nuclear medical diagnostic scanners for SPECT are technetium-99m, thallium-201, gallium-67, indium-111, and iodine-123 – all of which are single photon emitters. The emitted photons are viewed by large detector arrays which are moved around the patient to obtain a complete picture of the drug's concentration in the body. Together with the knowledge of how the drug accumulates in various anatomical structures of the body, one can assemble an image of those structures. SPECT systems have typical spatial resolutions of about 3 to 5 millimeters, and resolutions of one millimeter are theoretically possible. SPECT imaging technology and instrumentation is advancing rapidly making it competitive with standard computerized tomography.

Positron Emission Tomography

The Positron Emission Tomography (PET) imaging technique uses drugs containing small amounts of short-lived radioactive isotopes which decay by emitting the positively charged positron (β+, the anti-particle of the electron). When the emitted positron encounters an electron, the two particles annihilate each other by emitting a pair of photons in exactly opposite directions. In the body, this annihilation takes place right next to the location of the drug molecule which contained the β+ emitting nuclide. The two annihilation photons can be detected simultaneously with suitable radiation detectors, which are typically arranged in a circle around the patient. The line connecting the two detectors which fired passes through the point where the annihilation took place. By measuring the time delay between the two pulses one can pinpoint the location of the nuclear decay. PET scanners currently have resolution of the order of 5 to 8 millimeters. There is increasing emphasis on the use of short-lived isotopes such as oxygen-15 (half-life 2 minutes) to undertake the study of dynamical effects such as blood flow in the body (see Figure VIII.2).

PET devices can image the metabolic function within the human brain for neurological and psychiatric evaluations, the whole body for detecting cancer, or they can trace the metabolism in the heart and other organs. One can study the body in near-equilibrium by administering the positron-emitting nuclides very slowly with time, or one can study the body's dynamic response by administering the positron-emitting nuclides over a short time interval and by then observing its spread through the body with time. The radiation detectors are highly granular arrays of scintillators (to give the needed spatial resolution); dynamic studies require, in addition, the detection and processing of annihilation events at high rates. Physicists are presently developing ultra-fast PETs which could one day be used for on-line dose verification in cancer radiation therapy, allowing much more accurate dose administration than possible today.

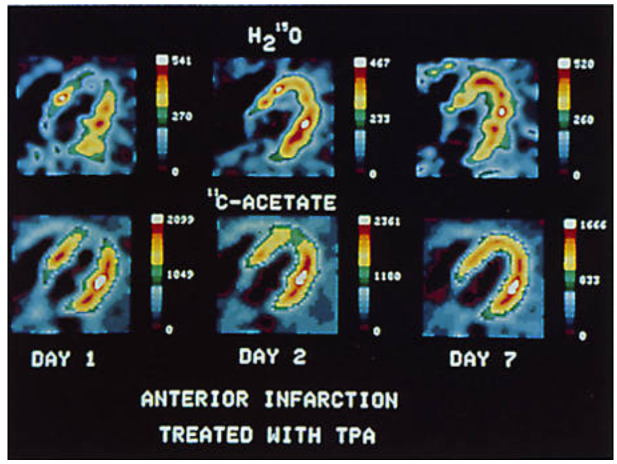

Figure VIII.2: The figure shows PET pictures of the heart of a patient with acute myocardial infarction treated with a thrombolytic agent. The top row shows scans after administration of water containing oxygen-15 nuclei to trace the blood flow. The bottom row shows tomograms obtained after administration of acetate containing carbon-11 nuclei to trace the heart's metabolism, i.e. its rate of oxygen usage. The defects are clearly visible on day 1, both in the impaired blood flow (top left) and the impaired metabolic use of oxygen (bottom left). Recovery of blood circulation has taken place on day 2 (top center) and is maintained through day 7 (top right). Defects in the metabolism are still visible on day 2 (bottom center); full recovery is seen by day 7.

MRI with Polarized Noble Gases

A very recent advance in some applications of nuclear magnetic resonance imaging (MRI) is the use of spin-polarized noble gases, such as helium-3 or odd-nucleon isotopes of xenon. The strength of the MRI image signal is proportional to the net spin alignment – which is small unless the applied magnetic field is very large. At room temperatures only protons and fluorine nuclei produce reasonably strong signals. Signals of sufficient strength have recently been obtained for other nuclei whose spins were pre-polarized externally by spin exchange with laser polarized rubidium gas. This technique was originally developed by atomic and nuclear scientists for nuclear physics research on weak interaction studies in nuclear decay and for polarized ion sources. Spin polarized helium-3 has also been used to provide polarized (bound) neutron targets, (see chapter I). In the course of these studies it was found that the spin polarization lasted for hours. For noble gases the nuclear spin alignment is largely independent of the atomic environment. As a consequence, the high spin alignment persists even when the gas is embedded in the tissue itself.

Seeing Inside the Body

Over the ages, physicians have sought a means of seeing inside the human body without cutting it open. Fundamental discoveries in physics have given us first x-rays and then the more modern diagnostic methods of magnetic resonance imaging (MRI) and positron-electron tomography (PET), contributing to remarkable advances in medical diagnostics.

The continuing development of MRI is illustrative of the intertwined path of basic physics and modern medicine. The technique began with research in nuclear physics — in particular the curious fact that the nuclei of most atoms behave as though they have a tiny magnet attached to them. Physicists soon learned that when they probed the properties of that magnet with a radio beam in the presence of a strong external magnetic field, they could identify which kind of atom it was. As the technique, known as nuclear magnetic resonance, improved, it became possible even to tell something about an atom's interactions with neighboring atoms. Chemists, initially at the State University of New York at Stony Brook and then elsewhere, developed the technique further as a powerful tool for analyzing the chemical structure of a material, including, eventually, biological tissues. This ability to probe the molecular structure of matter — and hence to map the distribution of certain kinds of molecules in a sample or of cancer cells in a body — provided the scientific base for MRI.

The result is a remarkable medical diagnostic tool. MRI gives the most precise picture now available of what is happening inside the body and yet does so noninvasively and safely. Even so, doctors and medical researchers would often like to know more. Seeing the lungs in action, for example, has always posed a particular challenge. And here physics has again

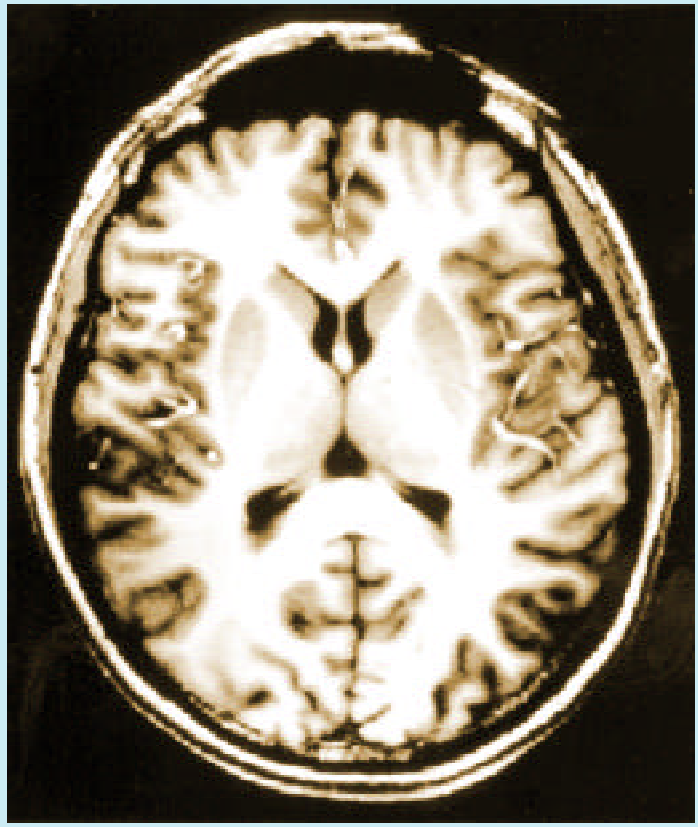

Figure VIII.C Axial (cross section) image of a human brain taken at high resolution, which clearly distinguishes white and gray matter as well as cerebral spinal fluid (the dark areas in the center of the picture). The images result from signals associated with the spin of the proton.

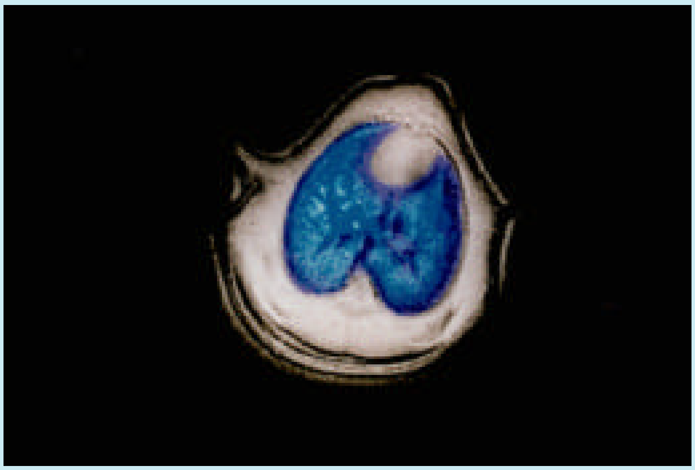

Figure VIII.D Magnetic Resonance Image (MRI) of a live guinea pig in thoracic cross section. The lungs (in blue) were imaged with inhaled He^3 with a nuclear polarization of 20%. Taken recently at Duke University, this is the first MRI image of living lungs made with polarized gas.

shown the way, as an unanticipated spin-off of basic research.

Polarized nuclei — those with an excess of the magnetic property known as spin — turn out to be very useful as targets for accelerated particles in basic studies of the structure of matter. So nuclear and atomic physicists have developed ways of making such polarized nuclei by using lasers tuned to emit light of precise wavelengths. The lasers "pump" or energize electrons, which in turn transfer some of their energy to the nucleus in ways that alter its spin properties. It turns out that certain isotopes of the noble gases helium and xenon — ^{3}He and ^{129}Xe — have both the spin properties needed for MRI and the atomic structure needed to retain their polarization for hours at a time. And these gases can be introduced into lungs, allowing MRI studies of how they are functioning.

In recent experiments, a group of atomic and nuclear physicists from Princeton and medical researchers from Duke used this technique to obtain the first MRI images of lung tissue in a living, breathing animal — a guinea pig. The experiments used ^{3}He, and because of the strong signal provided by the polarized nuclei in the gas atoms, the MRI scans took less than 20 seconds, synchronized to the animal's breathing. Using ^{129}Xe may allow clinicians to see even more biochemical detail. The high resolution MRI pictures obtained with polarized nuclei are the only imaging method now available for examining lung function. Human clinical trials are now being planned.

Thus the evolution of MRI imaging is once again entwining basic science and medical research. Princeton physicist William Happer points out that "if we had set out simply to find a better way to image lungs, we wouldn't have gotten this far."

In the first imaging application with spin polarized noble gases, polarized helium-3 was transported into the lungs of test animals. Figure VIII.D shows a magnetic resonance image of a live guinea pig in thoracic cross section. The figure illustrates that spectacularly strong images of the lung tissue (shown in blue) can be obtained. This is the first magnetic resonance image of a living lung ever made with laser polarized gas. The application of this technique is only in its infancy.

Trace-Isotope Analysis

Nuclear radioactive isotopes produced by accelerators or nuclear reactors are widely used in many areas of biological and biomedical research. These isotopes have chemical properties identical to their stable counterparts, but they decay, with known half-lives, by emitting characteristic radiation which is readily detected. 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 biochemical 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. They are also used to cure diseases; an overproduction of the thyroid (dangerous when left untreated) can be cured rather safely by having the patient swallow a controlled amount of radioactive iodine. 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.

Accelerator Mass Spectrometry

The highly sensitive method of Accelerator Mass Spectrometry (AMS) has made possible new uses of isotopes in the health sciences. In this method atoms from a minute sample are ionized and accelerated to a sufficiently high energy that atom-by-atom detection and isotopic identification with nuclear techniques becomes possible. By this means one can measure the concentration of a given trace isotope by directly detecting individual nuclei without having to wait for their decay. In virtually all applications the time available for observation in the laboratory is much smaller than the half-life of the isotope, i.e., only a small fraction of the nuclei can be detected via their radioactive decay. Conversely many more nuclei can be observed directly with AMS – therefore AMS has a much higher sensitivity, especially for long-lived isotopes that measure far into the past, than the traditional method of decay-spectrometry.

Because of its high sensitivity, the AMS method requires only very small quantities of tracer material and thus involves much reduced exposure to radioactivity than conventional tracer techniques. For example, carbon-14 can be used as tracer in biological systems with a sensitivity increased by a factor of one million beyond that possible with the more conventional method of scintillation counting. With this advantage one can determine the uptake of hazardous chemicals through the skin or measure the damage to DNA by carcinogens or mutagens at actual exposure levels. The amount of benzene, for example, from a single cigarette has been traced in vivo to the exact proteins in the bone marrow of mice that this toxin affects. By this means one can determine environmental hazards or safety risks of new (or old) pharmaceuticals without requiring (unreliable) extrapolations from unrealistically high doses. One can also use rare, but naturally occurring isotopes for research or diagnostics with human subjects in assessing disease states. For example, the long term progression of bone loss from osteoporosis can be studied at very low radiation exposure to the human subject by detecting minute amounts of the long-lived rare isotope calcium-41 (120,000 year half-life). Several other long lived isotopes are also available for toxic and nutritional studies. It is now possible to optimize the dose of a drug for an individual patient by measuring the fraction of an isotopic "tag" in excreted metabolites. Data from such low-level tracing experiments can be used to provide unprecedented insight into the biochemistry of the human body. Some thirty research groups world-wide have begun investigations in drug safety, toxicology, and metabolic processes using AMS. Extremely compact accelerator systems suitable for clinical or hospital AMS application are presently being designed and constructed.

Forensic Dosimetry

AMS makes it possible to measure the concentrations of long-lived isotopes produced by human activities long after the much more dangerous short-lived isotopes have decayed. This "retrospective dosimetry" is important for assessing the biological and environmental impact of events by obtaining a more accurate correlation between presumed radiation dose and the observed epidemiology in affected populations.

For example, retrospective dosimetry is being used to determine, with hindsight, the neutron exposures at Hiroshima and Nagasaki. In this way, scientists are able to resolve a very large discrepancy in the estimated neutron doses received by survivors. The discrepancy is largest far from the hypocenter where the doses are smallest. AMS is the only analytical method available to measure neutron activation at these large distances (e.g., by detecting small amounts of chlorine-36) and has provided crucial information. AMS will likely provide the final resolution to the Hiroshima neutron problem by reconstructing the fast neutron fluence via the determination of the nickel-63 content in copper wires recovered from the site. (Nickel-63 is produced when copper is exposed to neutrons – it has a half-life of about 100 years and is therefore still present.)

Important retrospective dosimetry studies are also being performed on some victims of the reactor accident at Chernobyl. The AMS technique can be used to measure the iodine-131 deposition in human thyroids, even after the isotope has decayed. So far, AMS is the only way to do this with the desired accuracy. The Chernobyl reactor released the isotopes iodine-129 and iodine-131 with well known relative amounts. Iodine-131 is much more dangerous if swallowed because it has a very short half-life (8 days), i.e., it is very radioactive. Although the iodine-131 deposition in the thyroid was measured for more than 100,000 people soon after the accident, the short half-life makes it impossible to repeat or extend these measurements at this late date, because the iodine-131 has decayed away. Since the half-life of iodine-129 is sixteen million years, it can still be detected long after the evidence for iodine-131 contamination has died off. Small amounts of iodine-129 can thus be measured to provide a dosimetry of thyroid exposure to the radioactive isotope iodine-131 released in the Chernobyl explosion. This makes it possible to reconstruct deposition patterns and thyroid doses some nine years after the Chernobyl accident.

In a related project, AMS is being used in a proof-of-principle test of an ultra-rapid detection of DNA rearrangements in the cell. Chromosomes broken by radiation or chemicals are recombined by the cell's repair mechanism, but some of these repairs produce incorrectly matched pairs. These erroneous corrections, called translocations, are stable throughout subsequent cell divisions. Chemical selection techniques, combined with carbon-14 tagging, make it possible to determine the frequency of translocations by measuring (via the ultra sensitive AMS) the carbon-14 content of DNA extracted from cells. From these measurements one can infer the received dose. If the technique is successful, damages associated with cancer induction could be detected rapidly, and it would be possible to redetermine exposure levels of large populations of workers that are subject to radiation and chemical hazards.

Environmental Science and Archeology

Nuclear diagnostic techniques find many applications in dating archeological objects, authenticating objects of art, and in monitoring changes in the environment, including the spread of man-made pollutants.

Archeology

Radiocarbon dating, invented by Willard Libby in 1949, has become an indispensable tool of archeology. Another important technique used for determining the concentration of rare isotopes in samples of archeological interest is based upon neutron activation at reactors. The Louvre Art Museum in Paris uses a 2 MV tandem-accelerator to authenticate art objects, largely by in-air PIXE. A submicron microprobe beam is available for special investigations which require high spatial resolution and which allow operation in vacuum.

In recent years, the invention of accelerator mass spectrometry (AMS) by nuclear physicists has created a revolution in archaeology almost as great as that of the original development of radiocarbon dating. By using a tandem accelerator to detect single atoms of carbon-14 rather than observing their decay, one can reduce the amount of

The Ultimate Sherlock Holmes

In the Conan Doyle thrillers, the peerless detective could tell at a glance which brand of cigarette had left the incriminating pile of ash. With a technique borrowed from nuclear physics, however, modern investigators can do far better. They can detect a few atoms of a trace constituent, allowing them to determine the age of ancient cave art — such as those recently found in France — identify the source of an environmental pollutant, or even measure victims' radioactive exposure from the Chernobyl accident nine years after the event. So sensitive is the technique, known as accelerator mass spectrometry (AMS), that even irreplaceable artworks can now be analyzed without harm to the original by using a nearly invisible amount of pigment — less than one thousandth of a gram.

The accelerator-based technique has been recently refined as applications have proliferated. Compact accelerators specifically designed for mass spectrometry are joining older accelerators recycled from earlier lives in nuclear physics research. In essence, the nuclei of the atoms that comprise a sample under investigation are accelerated, sorted by weight and element, and counted. Even trace isotopes — the radioactive ^{14}C instead of normal ^{12}C, for example — can be accurately distinguished. Since the proportion of different isotopes in a sample can help to reveal its source or age, such sensitivity is crucial.

In archaeological applications, for example, AMS has created a revolution almost as great as that of the original development of radiocarbon dating. Detecting individual atoms of ^{14}C rather than observing their radioactive decay is both faster and reduces the amount of sample needed by a factor of 1000. In geophysical studies, scientists use AMS to determine how long water from different parts of the oceans has been at the sea surface, allowing them to map circulation patterns that influence earth's climate.

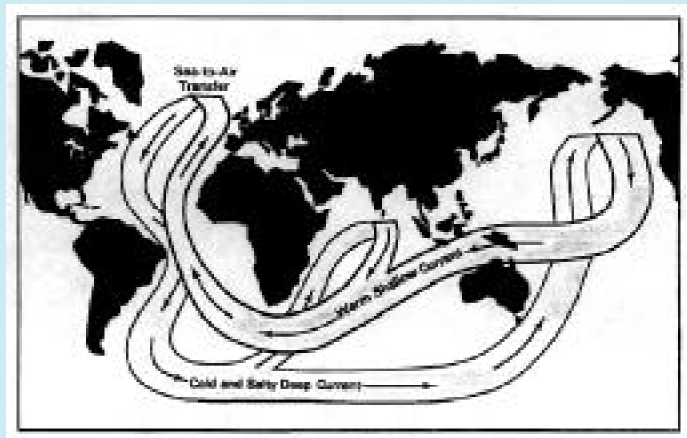

Figure VIII.E Accelerator Mass Spectrometry, a technique developed at low energy nuclear physics accelerators, has measured the age distribution of carbon dioxide dissolved in ocean water. This provides important information for understanding oceanic circulation patterns and their influence on weather and phenomena such as global warming.

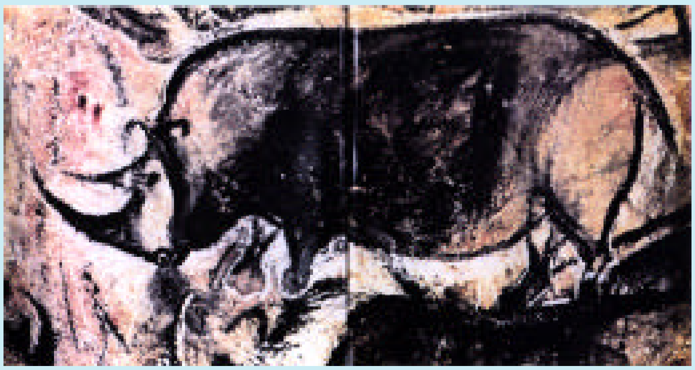

Figure VIII.F This cave painting of a long-horned rhinocerous and other paintings found in the south of France have overturned our ideas about the first appearance of art. Accelerator mass spectrometry has used minute samples to date such paintings as being made 30,000 years ago.

AMS also provides an ultra-sensitive method for detecting low-level seepage from nuclear waste sites before it becomes a significant environmental hazard. In fact, the technique is so sensitive that it is used to test compliance with nuclear nonproliferation agreements.

In the health sciences, AMS is making possible new uses of trace isotopes to study biomedical processes and to identify health risks. For example, scientists have been able to trace the amount of benzene (labelled with a radioactive isotope) from a single cigarette to the exact proteins in the bone marrow of a mouse that are affected by this toxic chemical. The ability to trace drugs or toxins at realistic levels of concentration could allow safety testing without using — and then extrapolating from — unrealistically high doses, as is often the case today.

Even Sherlock Holmes would have been impressed by the detective work done by scientists at the Lawrence Livermore National Laboratory to reconstruct, nine years after the Chernobyl explosion, how much radioactivity the populations living near the reactor had been exposed to. Much of that exposure came from ^{131}I, a radioactive iodine isotope that is absorbed in the thyroid gland. But because ^{131}I decays with a half-life of 8 days, determining the dosage received by an individual from this isotope was not possible. Chernobyl also emitted ^{129}I, however, which has a half-life of 16 million years. So by using AMS to detect ^{129}I, the Lawrence Livermore scientists were able to reconstruct the deposition patterns and the thyroid doses received by exposed populations for all forms of iodine.

Less than 20 years after its invention, the accelerator-based AMS technique is moving into the mainstream of investigative and forensic techniques — an unexpected spinoff of basic nuclear physics research.

organic material needed by about a factor of 1000 to less than one milligram. A tiny amount taken, for example, from seeds, pigments, food scales in pots, or animal matter on skinning tools is sufficient for an accurate determination of its age. One can also extract specific organic fractions from the material and determine the age for each fraction to assure that the specimen was not contaminated over millennia. Measurements taken at multiple excavation sites allow archaeologists to test their theories (provided that small samples of organic material can be found). One can also determine the age of artifacts in museum collections by removing nearly invisible amounts of organic material. Some thirty accelerator facilities world-wide now provide AMS measurements, more than half of them in support of archaeology.

Climate Change

The dramatically increased sensitivity of AMS has also provided scientists with an important new tool for solving problems related to global warming, air and water quality, and stratospheric ozone depletion.

Organic matter in soils and dissolved in sea water, though present in low concentrations, stores roughly four times the amount of carbon that exists in the atmosphere as CO_2. Besides being important in the carbon cycle, organic carbon in soils, sediments and solutions plays a major role in the mobility and toxicity of trace metals and other contaminants. In fresh waters, dissolved organic carbon contributes to the acid-base balance in lakes and streams. Recent measurements using the highly sensitive method of AMS have demonstrated that up to 50% of the organic matter stored in soils is turned over between soil and atmosphere on time scales of decades or less. Thus changes in terrestrial ecosystems, e.g., land use, and changes in atmospheric CO_2 content are interrelated and must be well understood for models of climatic change to have predictive power.

It is now possible to use carbon-14 dating for the exploration of ocean circulation patterns (up to a history of 50,000 years) and their influence on weather. The atmosphere continuously exchanges CO_2 with the oceans, which tend 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 sea water samples taken at various longitudes, latitudes, and depths allow researchers to create a three-dimensional map of the age of the oceans and to infer historical circulation patterns. This map also provides insight 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 to assess the significance of man-made CO_2 in the atmosphere.

AMS also provides valuable information about ground water resources by determining age and recharge rates of aquifers from their carbon-14 content – or, for very old aquifers, from their chlorine-36 content. AMS studies of the aerosols in smog can specify the relative contributions of wood burning and fossil fuel burning since wood contains carbon-14 and fossil fuels (which date back millions of years) do not.

AMS studies of radioisotopes such as beryllium-7 and beryllium-10 are contributing to an understanding of stratospheric ozone depletion. These beryllium isotopes are created in the stratosphere when cosmic rays strike nitrogen atoms, and they readily attach to aerosol particles. By studying the concentration of beryllium isotopes and the amounts attached to aerosol particles at different altitudes, one learns about 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.

Concern about a possible rapid climate change caused by man's activities makes it more important than ever before to study past climate changes on earth. An important component of these studies is the climate record stored in the Quaternary geologic archive. Here, AMS-based dating techniques have made a significant difference. Radionuclides suitable for such studies are beryllium-10, carbon-14, aluminum-26, and chlorine-36. These isotopes are produced by galactic cosmic rays, and they have half-lives ranging from about 5,700 years (carbon-14) to about 1,600,000 years (beryllium-10). For example, by determining the amount of beryllium-10 produced in the atmosphere and deposited in polar ice sediments, scientists can partially reconstruct the history of solar activity far back into the past. Cosmogenic radionuclides produced in surface materials tell about the history of glacial and debris flow. From these studies we learn more about the relationship between global changes, such as those recorded in polar and marine sediments, and more local, but nevertheless significant changes, such as alpine glaciation.

Most applications of AMS are today performed at dedicated accelerators. These are often refurbished electrostatic accelerators handed down from basic nuclear physics research, but increased demand has recently led to the design of more cost-effective machines that are specifically tailored to AMS applications. At the same time, new applications of AMS to isotopes of heavier elements are still being developed at basic nuclear research facilities. One example is the current effort to measure minute traces of the rare-gas isotope krypton-81 (at a level of less than one part in a trillion, $0.5\text{x}10^{-13}$) which could become a reliable chronometer of very old (50,000 to 1,000,000 years) ice cores, important for studies of past, long-term climate changes on earth.

Pollution Control

Nuclear techniques are employed routinely as diagnostic tools helping to reduce environmental pollution from coal-powered electrical plants by monitoring the chemical composition of the coal to be burned (e.g., 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 monitor the quality of coal at the mine directly and determine how to sort and blend it. They can then monitor and control the operation of coal preparation plants and determine the commercial value of coal to enforce coal contracts, and finally they can streamline the operation of power plants.

The PIXE and PIGE techniques described before are extensively applied to studies of air pollution, since it is possible to determine the constituents of haze in concentrations below 1 part per trillion, often permitting the identification of the actual source of the pollution.

Radioactive Waste

Significant amounts of radioactive waste material from the nuclear weapons program and also from the reactor industry are being held in temporary storage until a more permanent solution to the waste disposal problem can be implemented. Many sites at which nuclear weapons were fabricated and where large amounts of radioactive waste were kept in temporary storage now suffer from soil contamination. Physicists have developed a portable soil analysis system that employs nuclear physics detectors to measure the radioactive decay from trace amounts of plutonium. This detection system makes it possible to satisfy strict standards of soil purity during cleanup.

AMS techniques allow highly sensitive measurements of leakage into ground-water aquifers – or into the atmosphere. By being able to identify very tiny levels of contamination, it is now possible to pinpoint problems before they become a significant public health hazard.

Sterilization

Sterilization of food or medical products can be done, without destructive heating, by irradiation with X-rays. These are generated by commercially available electron accelerators, descendants of nuclear physics research machines. The process kills harmful bacteria, insects or larvae without destroying or activating the irradiated product; it is particularly important for materials (fresh food or certain plastic materials) which cannot be sterilized by high temperature heating. Electron beam treatment can also be applied to sanitize sewage sludge contaminated by hazardous organisms to produce hygienically safe organic fertilizer.

In some extreme applications, for example in the sterilization of pace makers, scientists are looking for still more effective techniques with less penetrating radiation to make sure that all bacteria are killed, but without damaging the irradiated material (e.g., the electronics of the pacemaker). Sterilization tests with proton or oxygen beams are being performed to establish irradiation standards and doses. The early results look very promising.

Space Science

The exploration of space is one of the most exciting human endeavors. Nuclear science makes important contributions to this effort. Detectors that are placed on satellites to probe the various radiations in space are first calibrated under controlled conditions with beams from nuclear science research accelerators. Possible health risks to astronauts due to cosmic radiation must be assessed by experiments at particle accelerators, and new detector technologies are being developed by nuclear scientists to unravel the mystery of the origin of high energy cosmic rays and to search for the apparently missing mass in the universe.

Calibrations of Detectors

Radiation detectors used on satellites must be carefully calibrated and understood before being launched. These calibrations require well-defined beams of photons, neutrons, protons, and/or heavier ions over a broad range of energies. The needed calibrations rely on the broad complement of nuclear physics research accelerators at Universities and National Laboratories which can provide the necessary calibration beams. Together with research reactors, these accelerators are an important part of the Nation's technical infrastructure which is essential for allowing rapid and broad advances in science and technology, in this case being an important prerequisite of many space missions aimed at obtaining a deeper understanding of the cosmos.

Beams of intermediate energy heavy ions from the National Superconducting Cyclotron Laboratory were, for example, used to calibrate the detectors of the EPACT (Energetic Particle Acceleration, Composition, and Transport) experiment on board NASA's WIND spacecraft (launched in 1994). Such beams are now being used for testing and calibrating large-area silicon detectors for NASA's Advanced Composition Explorer (ACE) mission (to be launched in 1997) and for developing a scintillation-fiber tracking detector for the Cosmic Ray Isotope Spectrometer (CRIS). The new instruments will measure the elemental and isotopic composition of galactic cosmic rays and of nuclei accelerated in solar flares. In another example, the Bates electron accelerator was used to produce monoenergetic photons with energies between 20 - 800 MeV for calibrating detectors for the EGRET/GRO experiment searching for the most energetic gamma-rays in the cosmos.

Space Radiation Effects: Space Travel Health Issues

In planning space missions of long duration, one must assess the health risk to astronauts due to ionizing radiation. Energetic ions in space are of three sources: particles trapped in the earth's magnetic field, ions emitted during solar flares, and very energetic ions produced and accelerated deep in the galaxy by still poorly understood mechanisms. The trapped radiation consists mostly of protons with up to several hundred MeV energy; it is restricted to the equatorial region and diminishes towards the magnetic poles. Manned orbital operations are restricted to low altitudes where the flux of particles is greatly reduced by interactions with the atmosphere. (For orbits at higher altitudes, lethal radiation doses can be accumulated within just a few days.) Some solar flares can produce large fluences of ions with energies up to 100 - 1000 MeV, but such events are rare. Galactic cosmic rays are less intense, but they extend to higher energies and contain significant numbers of massive, biologically more harmful ions (thirty percent of the biological exposure is due to iron ions alone). Since they are present everywhere in space, they pose the main limitation on long-duration manned operations in space.

Energetic heavy ions produce large biological damage, but the details are not yet well understood. An additional complication arises from the fact that the primary ions disintegrate into lighter, more penetrating ions as they travel through material; some of these disintegrations produce biologically very damaging energetic ions and neutrons.

Shielding can reduce the number of low-energy ions inside the space craft, but the most energetic radiation will penetrate any realistic amount of material. Protection from high-energy heavy ions is achieved by breaking them into smaller and less damaging fragments by nuclear interaction in the shield. In this process some constituents will be knocked out of the shield atoms and thus add to the exposure behind the shield. The composition of the penetrating radiation component depends critically on the nuclear properties of the intervening materials, but the production rates are not sufficiently well known to allow an accurate assessment of a given shield material. Further uncertainties arise from the fact that little is known about the health risks caused by high-energy neutrons produced by interactions in the shield material – or by interactions in human tissue itself.

The intermediate and high-energy heavy ion accelerator facilities at the National Superconducting Cyclotron Laboratory and at Brookhaven National Laboratory will be able to provide the data needed for understanding the health risks from cosmic radiation and for the optimum design of radiation shields.

Materials

Nuclear technology is widely used in basic materials research as well as in advanced industrial manufacturing. Based on accelerator concepts originally developed by nuclear and high-energy physics for fundamental research, beams of fast and slow neutrons and of light (photons) from synchrotron sources are now complementing research reactors as today's basic tools for the characterization of condensed matter systems. The experimental nuclear technologies of Rutherford backscattering and channeling are important quality assurance techniques in the semiconductor industry and for measuring the effectiveness of production procedures. In addition, neutron scattering experiments at research reactors have become an indispensable tool for deciphering the detailed structure of materials.

Theoretical tools developed for nuclear physics research find increasing applications in solid-state disciplines, especially in the rapidly progressing investigations of mesoscopic systems and metallic clusters.

Ion Implantation

Ion implantation is done by low-energy accelerators which are direct descendants of machines developed for nuclear physics. The ions are accelerated to modest energies (typically less than an MeV) so that they can be "implanted" into a thin layer of material close to the surface. Implantation of appropriately chosen ions can be used to modify, in a highly controlled fashion, the mechanical, chemical, or electrical properties of the material close to the surface.

Ion implantation is now universally used by the semiconductor industry which produces sales in excess of $100 billion/year. Ion implantation 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. Fabrication of the Pentium or Alpha computer chips, for example, relies on ion implantation; these devices could not be manufactured with the old diffusion technology. Ion implantation equipment sales world-wide are approximately $1 billion/year; the fastest growing segment of the market are MeV implanters used for deep implantation (total sales approximately $200 million/year). An example of an emerging technology based upon these higher energy implanters is the fabrication of SIMOX wafers, which are produced by implantation of 200 keV oxygen ions to create a SiO_2 layer. This technology is on the verge of being widely used; at least one commercial microprocessor chip is already made on SIMOX wafers.

A possible new application, still assessed by experimentation at nuclear science research labs, is deep implantation of ions using beams of several tens of MeV. For example, deep implantation of 30-50 MeV oxygen ions in GaAs and InP has been used to induce resistance changes of the materials; doping of these substances with 30-70 MeV Si ions has been used to create much thicker multi-layer photonic devices.

Single-Event Upsets

The performance of electronic devices can be strongly impaired by ionizing radiation. A charged particle intruding near a P-N junction may cause a "single event upset" (SEU) by generating excess electrons and holes which are then separated by the electric field of the junction and swept to a nearby device contact. If the collected charge exceeds a critical threshold value, the memory state of the device is changed unintentionally. Malfunctions due to SEUs become an increasing concern as the packing density of computer chips becomes larger. The understanding of SEUs is essential for the design of micro-computer chips, especially in space-flight or high-altitude military applications. For example, all microcircuits designed for space applications must pass "radiation-hardness" tests performed with light and heavy-ion beams which are presently provided by research accelerators.

Single event upsets are actively studied at several nuclear physics laboratories. At the 88-Inch Cyclotron at Lawrence Berkeley Laboratory "cocktail" beams have been developed which include nitrogen, neon, argon, krypton, and xenon, each of which can be rapidly selected by small adjustments. This method allow efficient tests of semiconductor devices with ions of different linear energy transfer (LET), the parameter of interest in SEU studies. Another, particularly novel technique involves the imaging of SEUs in integrated circuits by means of highly collimated ion beams (microprobes). When the microprobe beam is scanned across an integrated circuit, the beam generates both electrons and logic-state changes in the circuit which can be monitored by a computer. Visual images can depict both the physical appearance of the scanned region, through the ion-induced electron signals, and the areas of the integrated circuit that are susceptible to SEUs, through the detection of the chip malfunctions. With the experience gained from accelerator-based testing of SEU-related failures, the reliability of circuits against SEU failure has been improved by more than a factor of ten.

High-energy charged-particle radiation is an unavoidable fact of life for space missions. This radiation produces secondary fragments from nuclear reactions in the device. Recent research has shown that these secondary fragments play an important role in creating SEUs. This added complexity can, in principle, be treated by theoretical models, but the nuclear reaction cross sections needed as an input to these models are not well known. Experiments with beams from existing research accelerators provide the data needed to put these models on a solid footing.

Little information is available on the vulnerability of certain electronics chips on commercial jetliners which are exposed over a considerable amount of time to a moderate-intensity neutron-radiation environment from cosmic rays. A major airline company has recently tested the chips in question at the Los Alamos Weapons Neutron Research facility which can generate a neutron distribution very similar to the cosmic-ray neutron spectrum, but with 100,000 times the intensity.

As the individual components for micro-circuits become ever smaller and tightly packed, SEUs caused by alpha-particles emitted by material impurities become a serious concern. Nuclear experiments searching for rare events such as solar neutrinos and double beta decay are pushing the technology for producing low-radiation materials. Using technologies developed for the Sudbury Neutrino Observatory and elsewhere, nuclear scientists have recently developed an ultra-low alpha-particle background sensor which allows the screening of micro-electronic circuits for alpha-particle emitting contaminants with 10 - 100 times the sensitivity of systems currently in use.

Material Analysis

Nuclear techniques are widely used in the analysis of the composition and properties of materials, the structural integrity of manufactured parts, and their wear while in use.

Rutherford Back-Scattering

Detailed material compositions close to the surface are explored most conveniently by the Rutherford backscattering spectroscopy (RBS) technique. This well-established diagnostic tool utilizes projectiles of sufficiently low energy (typically a few MeV) so that only elastic scattering will occur. The scattered particles are detected in a well defined geometry in the backward direction. The particles lose energy both in the elastic collision process (this depends on the mass of the collision partner) and in ionization processes in the target material (this depends on the path length of the particle in the material). A measurement with sufficient energy resolution can thus provide information both on the mass as well as on the depth distribution of target nuclei. RBS has become an important tool for studying the composition, structure, and thickness of material surfaces as well as the depth profiles of impurities near surfaces. The most frequent application of RBS is in the analysis of materials for the electronics industry.

Proton-Induced X-Ray and γ-Ray Emission

Proton-induced X-ray or γ-ray emission (PIXE or PIGE), are highly sensitive complementary techniques derived from nuclear physics that are suitable for elemental analyses of tiny amounts of material. PIGE is based on the detection of the prompt γ-rays emitted following a charged-particle-induced nuclear reaction. This technique is most frequently used in the analysis of light elements. Due to the increasing energy of X-rays over the periodic table, the PIXE technique is more suitable for the detection of heavy elements.

Strongly collimated proton beams ("microprobes" with beams spots of 0.0001 inch diameter or less) from dedicated electrostatic accelerators are finding increasingly varied applications, e.g., in biomedical research or semiconductor and geological analyses. For example, a group of scientists at Oxford University used a microprobe to show that there is no link between aluminum intake and Alzheimer's Disease.

Non-Destructive Testing

Nuclear technology finds many applications in non-destructive testing, an estimated $300 million/year industry. Just as medical imaging shows the interior of the human body without surgery, industrial imaging using nuclear techniques and detectors reveals the interior of equipment without disassembly. For example, radiography with neutrons (either from a reactor or from a californium-252 source) permits the sensitive detection of potentially dangerous corrosion inside an airplane wing without the need to take it apart. 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.

Advanced CAT scanning devices have been employed to scan metal parts and detect cracks hidden in bulk material (e.g., an automobile engine block or a turbine blade) which could lead to early fatigue. For example, it has been possible to detect cracks which are hidden as deep as 10 inches inside a casting. It is also possible to diagnose the thickness of materials by analyzing back-scattered gamma-rays. By this means one can check old boiler tubes or bridge girders for structural weakness.

By introducing tiny amounts of radioactive material into the surfaces of engine parts the wear of moving parts (e.g., an engine piston) can be diagnosed with high accuracy by analyzing the tiny amounts of radioactive tracer material in the engine oil – without having to stop operation of the engine.

Ion-Induced Secondary Ion Emission

For more than twenty years irradiation with fission fragments from californium-252 fission sources has been used to produce secondary ions of large, fragile biological molecules. The impact of one of the two fission fragments causes the desorption of the molecule. The other fragment, emitted into the opposite direction, is used to obtain the start signal for a time-of-flight spectrometer. Such devices have become ubiquitous in the field. Evolutionary variants of this basic desorption technique now involve lasers, energetic ion beams (with energies in the MeV range), and beams of clusters as the agents of the desorption process. Each new development has greatly extended the mass range and sensitivity of the technique, which was a direct offshoot of basic work in nuclear science.

Muon Spin Rotation (μSR)

Muon spin rotation (sometimes referred to as relaxation or resonance), is the name used to describe a collection of experimental techniques based on the (parity-violating) decay of spin-polarized muons. The technique was first used for precision tests of quantum electrodynamics, but has now become a versatile and important tool of chemistry and materials science. The muon's magnetic moment provides a sensitive probe of local magnetic fields which can be used to investigate the microscopic magnetic properties of materials, the electronic structure of hydrogen isotopes in matter, and the quantum diffusion of light interstitial impurities. For example, μSR is well suited for the characterization of high-T_C superconductors and their parent compounds because the muon can "passively" probe the internal magnetic fields in metals or superconductors. The μSR technique also provides important tests of the theory of chemical reaction kinetics since it is relatively easy to investigate the chemical reactions of the muonium atom (μ^+e^- or Mu), a light analog of hydrogen. Free radicals formed by the addition of hydrogen can often be studied with greater precision and versatility by means of μSR techniques than by any other method, and several new radicals have been discovered by μSR. Studies of μ+ and Mu diffusion provide the best experimental tests of modern theories of quantum transport with dissipation which are important in many areas of solid state physics. Another important application of the μSR technique is the study of hydrogen point defects in the commercially important semiconductors silicon and gallium arsenide: μSR experiments have provided much of our present understanding of the structure and dynamics of hydrogen in these semiconductors.

Material Modifications

A variety of irradiation techniques are used to modify the properties of materials.

Flux Pinning in High-T_C Superconductors

Ion beams and neutrons are being used in experimentation on and improvement of high-temperature superconductors. Current vortices form spontaneously in these superconductors upon application of a magnetic field. Each vortex is a tiny cylinder of magnetic field surrounded by circulating super-currents. In order to maintain zero resistivity at high electrical current densities, one must immobilize ("pin") the vortices spatially. Pinning centers produce magnetic ingots which retain the highest magnetic field of any material at any temperature ("trapped field magnets", TFMs). The development of methods which allow improved pinning of vortices in superconductors is thus very important for any application using superconducting magnetic devices (e.g., miniature motors or magnetic levitation devices).

Heavy ion tracks, long column-shaped defects produced by irradiation of superconductors with energetic heavy ions with energies of 5 - 100 MeV per nucleon, are now recognized as the most effective vortex pinning defect yet discovered. Because of their unusually strong pinning, these columnar defects profoundly alter the static and dynamic behavior of vortices. For example, columnar defects produce new phases of vortices. In the case of tracks along the c-axis of a YBCO crystal (a particular high temperature material) a new glassy phase ("Bose glass") results. If tracks are introduced at angles of 15° relative to this axis a "splayed glass" phase results that has a very large increase in the critical current. It appears that the pinned vortices are entangled in the aligned defects and are thus immobilized – hence they do not contribute to the resistivity. New dynamical effects (e.g., the hopping of vortices from one columnar defect to the next or recoupling into 3-dimensional "string" vortices which are more easily pinned) have been discovered or at least predicted, and they promise to teach us much about the basic science of strong pinning and how to implement it for applications. The study of ion-induced pinning centers, and the prototyping of various devices using trapped field magnets, is being actively pursued world-wide.

Surface Modifications

Ion implantation is being developed for producing very hard surfaces for machining tools with much improved performance and lifetimes, and for manufacturing materials with corrosion-resistant surfaces. A related technology is irradiation by X-rays or electrons to modify the surface properties of plastic materials (e.g., adhesive tapes or floppy disks) and polymers (e.g., foamed polyethylene, heat shrinking tubes and sheets). This process is environmentally friendly as it does not produce chemical pollutants.

Free Electron Lasers

The invention of the laser as an intense source of monochromatic and coherent light has had a profound impact on many areas of science and technology. Many new applications are, however, hampered by the difficulties of conventional lasers in producing monochromatic light over a broad range of wavelengths from infrared (IR) through visible to ultraviolet (UV) and in producing and sustaining, with large duty factor, extraordinarily high power levels due to excessive heat generation in the "lasing" medium. Free electron lasers, developed originally at the HEPL nuclear physics superconducting test accelerator at Stanford University, can overcome these limitations. As the most recent example, electron accelerator technology carried out at the Continuous Electron Beam Accelerator Facility (CEBAF) using superconducting radiofrequency cavities can provide a driver for a tunable free electron laser (FEL) of high average power which can serve as a highly versatile industrial light source at lower per-unit cost than alternative light sources currently available. Some Van de Graaff accelerators and low-energy (40 to 70 MeV) electron accelerators are already being used for FEL production of tunable radiation in the infrared and visible range.

Industrial interest is growing worldwide for the potential applications of FELs. Intense light at the appropriate wavelength has a demonstrated ability to alter the chemistry, topography, and morphology of materials, surfaces, and interfaces. For example, one can modify the surface of polymer films, fibers, or composites to improve adhesion, enhance the ability to take up dyes, or enhance the effectiveness in filtration uses. At present, the chemical industry uses wet chemistry to impart such surface modifications, with a substantial burden on the environment. The replacement of a wet-chemistry process with one driven by an FEL will provide a substantial environmental benefit.

Micropore Filters

Filters with microscopic pore sizes can be produced by irradiating polycarbonate films of some 10 μm thickness with heavy-ion beams of low-energy (e.g., iodine of 75 MeV energy and with some 10^{11} beam particles per second intensity). The heavy ions produce radiation damage in the substrate. After irradiation, the foils are etched to give the desired pore sizes. The technique has the great advantage of producing very uniform pores with parallel tracks. Pore densities can be varied over nearly 4 orders of magnitude. Currently the technology is employed at the Tandem Facility of Brookhaven National Laboratory to produce filters which find a wide range of applications, such as the filtration of bacteria, viruses and proteins, the production of ultra-pure water (needed by the semiconductor industry), quality control in the wine industry and other industries requiring yeast, mold and bacteria analyses. Many other specialized applications exist in the pharmaceutical, clinical and food and beverage industries.

Mesoscopic Physics

Many ideas from nuclear physics have been applied to the study of mesoscopic condensed matter systems (which consist of tens to thousands of atoms, in contrast to macroscopic systems containing more than thousands of trillions). For such systems, the discreteness of electron single-particle levels leads to interesting phenomena which often have analogies in the theory of compound nuclei (i.e. systems formed by fusing two nuclei together). Examples are conductance fluctuations in small wires and quantum dots. The various observed fluctuation phenomena can be described by approaches very similar to theories developed in nuclear physics, namely, random matrix models, precompound models, and Ericson and Porter-Thomas fluctuations. In addition, shell model nuclear physics and its semi-classical description have been found to be related to the phenomenon of persistent currents in mesoscopic rings. The magnitude of these currents depends on an interplay between the regular spectra of the shell model and chaotic spectra of disordered systems. These few examples illustrate that progress in science is often made by transferring both theoretical and experimental tools from one field to another, seemingly unrelated, field. Other striking examples are studies of quantum corrals and atomic clusters.

Figure VIII.3: An "atomic stadium" made visible by scanning tunneling electron microscopy. Iron atoms (shown in blue) form the walls of the stadium; the interior electron distribution is shown in orange.

Quantum Corrals

Studies of chaos attempt to explain and find the limits of predictability of seemingly random phenomena like earthquakes, turbulence, the weather. During the last few decades much progress has been achieved for large ("macroscopic") systems which are governed by classical mechanics. For very small ("microscopic") systems on the atomic scale, chaotic behavior is further complicated by the fundamental limitations imposed by quantum mechanics, such as the impossibility to simultaneously determine the exact location and velocity of a particle. This area of study has been called "quantum chaos", and nuclear scientists have made and are making seminal contributions to it. This emerging field is important for a key technology of the next century, the production of ever-smaller devices down to atomic scales. This is known as nano-technology and quantum engineering.

One prominent recent example of quantum engineering is the construction of "quantum corrals", i.e., the manipulation of individual atoms to construct electron-confining regions of specific shapes. The example in Figure VIII.3 shows the electron distribution in an oval-shaped quantum corral ("atomic stadium") assembled from indi-

Making Defects To Improve Performance

Ever since the Nobel Prize-winning discovery of high-temperature superconductors in 1986, visions of powerful new technologies have danced before engineers' eyes like so many sugarplums. So far, however, superconducting applications that could transmit and store energy more efficiently as well as enable highly efficient motors or other novel devices have proved elusive. But thanks to nuclear accelerators, a major hurdle to widespread commercial use of high-temperature superconductors is now being overcome.

The problem has been in coaxing high-temperature superconductors to carry large currents of electricity without losing their superconducting properties. In the presence of a magnetic field, superconductors form internal magnetic fields — known as vortices because each tiny cylinder of field is surrounded by a circular flow of current — that can move about and disrupt the overall flow of current. Immobilizing or "pinning" these internal magnetic fields is the key to high superconducting currents.

Materials scientists have found that defects in a material can pin the internal magnetic fields and thus, paradoxically, improve its performance. Two recent discoveries — new ways to create defects — have led to dramatic increases in the amount of current superconductors can carry. The first came from irradiating superconductors with accelerated heavy ions for short periods, as little as one minute, in the process creating precise, parallel, microscopic tracks or grooves in the mate-

Figure VIII.G The Holifield accelerator at Oak Ridge National Laboratory is an example of an accelerator, normally used for basic research, where flux-pinning of superconducting material has been carried out.

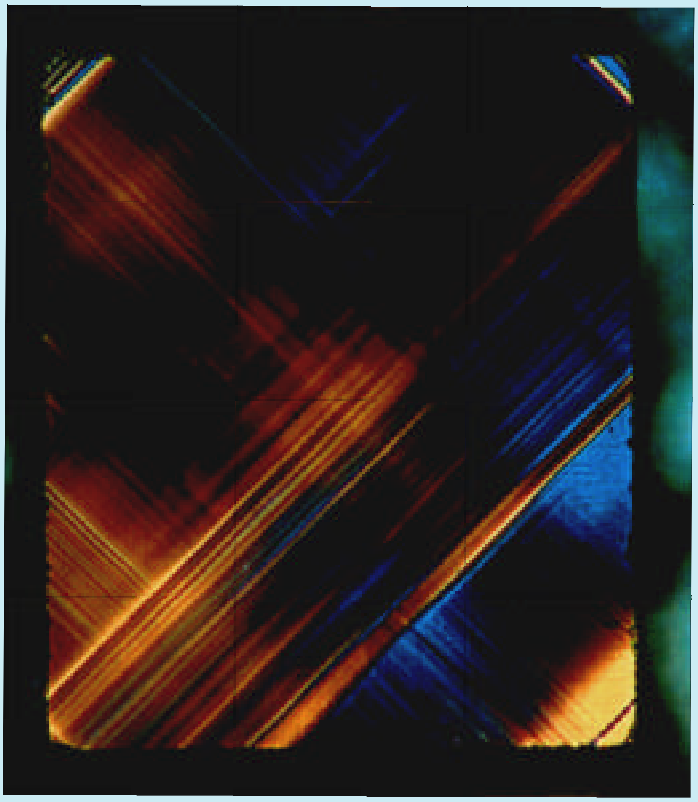

Figure VIII.H Single crystal of a high-temperature superconductor (the colored stripes are naturally occurring planar defects visible in polarized light). Heavy-ion irradiation adds artificial defects, which enhance the critical current by "pinning" the magnetic flux lines which otherwise move freely in the superconductor. Improvements by a factor of 10 have been made with exposures of as little as one minute to a heavy-ion beam.

rial. These engineered defects increased the maximum current in the material by up to a factor of ten.

More recently, scientists have discovered a second technique, also borrowed from nuclear physics. The superconducting material is irradiated with high-energy protons, which split some of the atoms into fragments. The fragments from each such collision, like shrapnel from an explosion, create multiple tracks in random directions through the material. These randomly-oriented tracks improve current-carrying properties in all directions within the material, a valuable feature for many applications, and also increase the maximum current even more than the parallel tracks from ion beams.

As a result of these discoveries, nuclear accelerators are playing a critical role in moving the field ahead. Studies of the defects created by different irradiation conditions and their effects on internal magnetic fields within superconductors promise to teach scientists the secrets of effective pinning and how best to make use of them in practical applications of superconductivity. The hope is that a way has been found to bring to fruition the promise of high-temperature superconducting materials. The ability to engineer much higher current-carrying capacity into these materials may well enable their commercialization in applications ranging from long-distance electrical power transmission lines to improved medical imaging devices.

vidual iron atoms and made visible by a scanning tunneling electron microscope. This distribution is well described by the theoretical tools and methods developed and perfected by nuclear scientists.

Atomic Clusters

The study of atomic clusters (typically made up of thousands of atoms or less) has blossomed since the mid 1980's when it was discovered that clusters containing certain "magic" numbers of atoms were much more abundantly produced than others. This initially perplexing experimental observation could be understood by theories largely adopted from nuclear theory. Nuclear theorists predicted, for example, a new shell phenomenon for large systems, the "supershell". Its existence has seen spectacular confirmation in experiments on sodium clusters, which show shells extending up to thousands of atoms. Another example of cross-disciplinary connection is the well-known giant dipole resonance in nuclear physics which has a close analog in the Mie resonance of simple metal clusters. Many of the properties of the Mie resonance were anticipated from the nuclear example: splitting due to deformation, thermal broadening, and the existence of a collective mode of excitation in a cluster of sixty carbon atoms, C_{60}.

The nuclear physics stimulus has led to new directions in cluster reaction studies, such as the fission of charged clusters or their fragmentation by high-energy probes. The data show intriguing similarities to nuclear fragmentation, and they can be rather well described by a percolation model originally developed for nuclear fragmentation.

Electrostatic accelerators are being used to produce beams of gold and carbon clusters with energies in the MeV range. When such energetic clusters interact with materials they produce damage far in excess of that produced by heavy ions. In addition, the collective behavior in cluster ion impacts is more efficient in producing secondary ion species – which finds an important application in the mass spectrometry of large biological molecules.

Rare gas clusters, especially helium-3 and helium-4 clusters, are even more like nuclei in that they are dominated by short range interactions. Nuclear theorists have pioneered the study of quantum helium liquid droplets by exact quantum Monte Carlo methods and continue to play a significant role in the current research program on impurity scattering and laser spectroscopy in both physics and chemistry.

Safety and National Security

Nuclear technology has many applications which make our lives safer. Examples range from simple smoke detectors which contain a small radioactive source to detect changes in the ionization of air, to sophisticated scanning systems which use penetrating radiation (neutrons or energetic photons) to detect bombs or contraband, to highly sensitive isotope detection techniques used for arms control and nonproliferation verification.

Airport Safety

Experimental nuclear techniques may provide new sophisticated security tools for the detection of narcotics and explosives. Systems based on thermal neutron analysis are able to 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. By detecting the known high-energy γ-rays which are emitted when neutrons are captured by nitrogen nuclei one can obtain a unique signature for the presence of nitrogen – a key element in most explosives (and wool fabrics). By this means it is possible to augment existing X-ray scanning machines which are primarily used to detect metal objects, but which do not allow unique identification of nitrogen atoms or other light elements. A more sophisticated system, known as pulsed fast neutron analysis, is under development; it uses detectors and computers to produce a high-resolution, three-dimensional picture of the inspected volume. Specifically tailored compact accelerators can provide the required compact, low-risk, and transportable neutron sources. By necessity, the required neutron generators would require the implementation of strict radiation safety measures when installed at public places. This complication must be weighed against the resulting benefit of enhanced security against terrorist activity.

Large-Scale X-Ray and Neutron Scanners

Diagnostics with X-rays or neutrons are widely used, e.g., to detect weapons or contraband concealed in airport luggage, early signs of stress

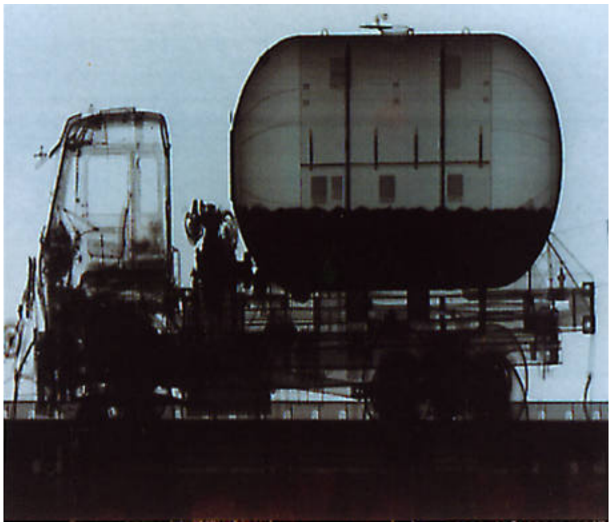

Figure VIII.4: Large-scale X-ray scan of a tanker truck revealing the fill level of the tank. Such systems can be used to detect car-bombs at highly vulnerable transportation centers.

fractures in materials, etc. The widely used californium-252 neutron sources are produced at nuclear reactors. Modern nuclear detection technologies are presently being incorporated into large-scale X-ray systems which generate images digitally, rather than by the traditional use of film material. An interesting recent application is the development of a large high-energy X-ray scanner consisting of a 5 MeV, 500 μA electrostatic electron accelerator plus associated digital detection system, all computer controlled and interfaced. The electron beam strikes a rotating target to produce the X-rays. Cargo trucks or containers pass between the X-ray beam and the detection system. Real time image processing allows inspection of over 20 trucks (up to 18 m long) in one hour.

The system is capable of imaging extremely small objects inside large containers for detection of weapons or other controlled or dangerous contraband (see Figure VIII.4). Such systems are useful for security at highly vulnerable transportation centers.

Arms Control and Non-Proliferation

Nuclear techniques are of prime importance in two areas of arms control: monitoring the progress in and compliance with treaty provisions on the limitation and destruction of nuclear weapons, and detecting attempts by proliferant or terrorist states or organizations to manufacture, acquire and transport nuclear materials and weapons. The US and Russia are committed to disassemble 2,000 - 3,000 warheads per year over much of the next decade. In order to keep track of existing weapons and assure that plutonium and enriched uranium from disassembled weapons are not recycled into new weapons, one must rely on nuclear detectors and data handling systems derived from the best of current research techniques – and upon well trained experimental nuclear scientists to do the necessary work. Of particular importance is the ability to work with “less than perfect” solutions dictated by political compromises balancing one party’s need against the other party’s desire to protect sensitive information.

Often, the monitoring of chemical weapons agreements uses nuclear analysis techniques. Since warheads containing chemical weapons and 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.

Many sites at which nuclear weapons were fabricated now suffer from soil contamination. Unusual concentrations of the isotopes hydrogen-3 (tritium) and carbon-14 may reveal undeclared reactor operations. The isotopes chlorine-36, technetium-99 or iodine-129 may leave tell-tale traces from undeclared reactor fuel reprocessing operations. Accelerator mass spectrometric techniques have the sensitivity to detect these long-lived isotopes at the ultra-low concentration levels likely to be found in samples taken for environmental monitoring.

Energy Production

Initially power production from nuclear fission reactors was the main contribution of nuclear physics research to the nation’s energy needs. Today the scope of nuclear physics contributions has widely expanded. Methods and techniques developed by nuclear physicists provide a broad spectrum of applications to energy-related problems, e.g., monitoring and discovering conventional energy sources, improving the reliability of nuclear power plants and advancing improved designs, and contributing to the long term goal of fusion energy power plants.

Nuclear science continues to develop 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 the disposal of radioactive waste in a world that already obtains one fourth 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.

Oil-Well Logging

When a well is drilled to discover oil or gas reserves, one must be able to determine if oil or gas is present. To evaluate the contents of the rocks drilled through, a variety of instruments employing electrical, sonic, and nuclear techniques are lowered into the well, contained in a housing designed to withstand pressures of up to 20,000 PSI and temperatures of up to 175°C, typically at the end of a 5 mile long cable. This technique of "well logging" has significant impact in scientific drilling studies that aim at a better understanding of the geology deep in the earth and at finding mineral deposits. However, its most significant application is in the exploration for oil or gas. (An interesting variant of the technique has recently been developed for studying the density and depth of the Arctic permafrost in the northern parts of Canada.) Oil-well logging is a business with more than $1 billion/year in gross revenue.

Many of the nuclear well logging measurements use compact neutron generators (about 1 inch in diameter) and a variety of gamma-ray detectors. Nuclear well logging involves many different techniques such as gamma-ray scattering (allowing the determination of the bulk density of the rock), neutron scattering (allowing the evaluation of the amount of pore volume in the rock that may contain fluids) or measurements of (n,γ) reactions (allowing the evaluation of rock mineralogy and the detection of oil, gas, or water). The final data analysis, combining the results of the different measurements, produces a real-time log of the results as function of depth, typically with measurements every 15 cm.

The most widely used technique is based on the inelastic scattering of γ rays from a cesium-137 source; it allows measurements of the formation density with a precision of $\sim$0.01 g/cm^3. This measurement is an essential ingredient in the determination of the porosity of the rock, i.e., the fluid- or gas-containing fraction. Another technique uses compact electrostatic deuterium-tritium neutron generators to produce 14 MeV neutrons which then scatter inelastically from carbon and oxygen. By detecting the characteristic γ-rays emitted from the excited carbon and oxygen nuclei, one can determine the relative abundance of oil and water (after correcting for carbonate rock-formations). Such measurements are used to monitor the oil saturation and reserves in producing wells and to determine the optimum depths for tapping the oil in freshly drilled wells.

Fusion

For more than 50 years, scientists and engineers have recognized that nuclear fusion, the source of energy that fuels the sun and the stars, might be harnessed on earth to provide a virtually limitless, environmentally acceptable source of energy. Low-energy accelerators that have evolved from nuclear science are important in the fusion power program, both for producing the beams of neutral particles that are used to heat the plasma and for producing intense neutron beams used to test materials that will be incorporated into plasma fusion reactors.

Recently, the Tokamak Fusion Test Reactor (TFTR) at Princeton started the first sustained campaign to operate with a mixture of deuterium and tritium predicted, from nuclear physics data, to produce a larger energy release than pure deuterium fuel. Measurements of the neutrons produced in these tests confirmed that this was indeed the case. The neutrons were measured with nuclear activation techniques.

The traditional role of nuclear science in fusion research has been to provide fundamental nuclear data, but the field is now contributing to fusion research more directly. There are common areas of technology such as the large-scale application of superconducting devices and instrumentation. Perhaps more importantly, a commercially viable inertial-fusion power plant is likely to depend on heavy ion accelerator technology.

In inertial fusion, intense beams from a laser or an accelerator (a "driver") are directed onto a tiny capsule containing a few milligrams of thermonuclear fuel (typically a solidly frozen deuterium-tritium mixture). The beam energy produces an implosion that compresses the fuel to about 1000 times its solid density. The implosion also heats the fuel to about 100,000,000 degrees. At this high temperature the fuel ignites, releasing a huge amount of energy. This process, if repeated several times per second, could produce enough energy to drive a large power plant.

Lasers can readily produce intense bursts of light focused into a tiny spot: therefore, most of the scientific (and military) research in inertial fusion has used lasers rather than accelerators as drivers. Existing laser facilities at Lawrence Livermore National Laboratory and the University of Rochester have made major contributions to understanding the implosion process necessary for developing the target technology. The laser technology is now available to achieve ignition, a major milestone along the road towards inertially confined fusion as a potential commercial power source.

An essential next step will be the development of a driver capable of the high repetition rates of several pulses per second needed for a demonstration power plant. Present state-of-the-art lasers are excellent research tools, but they suffer from low repetition rates (typically only a few "shots" per day) and relatively low energy-conversion efficiency. Experience with accelerators for nuclear science, extensive theoretical calculations, computer simulations, and a growing body of experiments indicate that heavy ion accelerators should be able to produce heavy ion beams (such as Sn or Bi of about 50 MeV per nucleon energy) of sufficient intensity to serve as inertial fusion drivers and that such accelerators may be able to meet the other requirements for commercial energy production, namely high repetition rates, reliable operation and long lifetime, and high energy-conversion efficiency. This approach is known as heavy ion inertial fusion. In France, scientists are considering the possible use of even heavier ion-beams, e.g., energetic beams of the molecular cluster C_{60}, to drive inertial fusion.

Larger experiments are needed to confirm fully that accelerators can produce heavy ion beams with the required intensity and beam profile. The U.S. Department of Energy plans to build a heavy ion accelerator at Lawrence Berkeley Laboratory specifically for fusion research. The investment over many decades in accelerator technology for nuclear and particle physics and the investment in laser fusion for defense provide the basis for this potentially important technology.

Nuclear Reactors and Accelerator-Driven Neutron Sources

Intense sources of neutrons are important for many areas of basic and applied research (e.g., condensed matter physics, materials research, medicine, space physics), as well as for aspects of national security.

Traditionally, intense neutron sources have been provided by nuclear fission in research reactors, of which more than 300 are in operation worldwide. The reliability and availability of research reactors have proven to be very high. At present, the world's most powerful neutron research facility is the high-flux reactor at the Institut Laue-Langevin (ILL) in France. There is strong international interest in significantly higher neutron fluxes for both basic and applied research.

Accelerator physics techniques can play an important and complementary role for the production of intense sources of neutrons. In one technique sharp pulses of neutrons are produced by powerful electron beams impacting a heavy metal target; sometimes a subcritical fissile or fissionable target material is used to boost production. The average neutron flux is limited by the heat deposited in the target ($\sim$2000 MeV per neutron produced as compared to $\sim$100 MeV per neutron in a fission reactor), but the ability to generate sharp pulses, so that neutron energies can be accurately determined by time-of-flight techniques, is very advantageous for certain measurements (e.g., for cross section measurements). This technique produces less long-lived radioactive waste than a fission reactor (except when a booster target is used). In addition, neutron production can be terminated by shutting off the electron beam, so that an uncontrolled chain reaction is not possible.

An alternative accelerator technique employs a high energy (typically $\sim$1 GeV) proton beam to generate neutrons by spallation reactions. The needed accelerator is more costly than an electron machine, but the technique has the advantage of reduced heat production in the target ($\sim$30 MeV per neutron). Thus, the way is open for the development of sources with an average flux comparable to a high flux reactor and with a much higher instantaneous flux during the pulse, without exceeding practical heat removal capabilities. The time-bunched structure of the bursts can again be used to provide additional information. At present, the world's most powerful spallation source is the 200 kW ISIS facility in Britain. This facility produces a lower thermal neutron flux (both average and peak) than many research reactors, but its advantageous timing capability makes it complementary to reactors for some experiments. A spallation source of 5 MW would match the capabilities for neutron scattering experiments of the best reactor.

In both fission and spallation sources, the neutrons are slowed down to the desired energies by scattering off appropriate moderator-reflector assemblies. Reactors operate in a continuous mode; they produce high integrated fluxes of cold and thermal neutrons ($\sim$ 0.001 - 0.1 eV). Spallation sources are most effectively operated in a pulsed mode (10 - 100 Hz); they give high instantaneous peak fluxes of thermal and epithermal ($\sim$ 0.1 - 10 eV) neutrons which is of advantage for time-of-flight scattering experiments.

Reactor and spallation-based neutron sources each have unique capabilities; the two types of sources are thus complementary and mutually supportive. Experiments requiring high integrated flux, especially of cold neutrons, are best performed at a high-flux reactor. Examples include activation analysis, neutron depth profiling, and cold neutron radiography. On the other hand, experiments requiring high-energy neutrons or a high instantaneous flux are best performed at a spallation source. Examples are resonance radiography, high-energy transfer spectroscopy, diffraction measurements that require high neutron energies, and time-of-flight spectroscopy.

Nuclear reactors and high-intensity accelerators also play an important role for the production of radioisotopes. Neutron rich isotopes are most economically produced in nuclear reactors; neutron poor isotopes are best produced by proton bombardment.

Cold and Ultra Cold Neutrons

Cold neutrons are especially important for studying the properties of materials in the region between the surface (the first few layers of atoms) and true bulk matter (deep into the material). This transition region determines a number of interesting material properties and is particularly important for many advanced composite materials. In many cases, neutrons provide the only means to probe this interface region. Present techniques rely on reflectometry, i.e., measurement of cold neutron scattering from the material at a very small angle. This requires very high precision and limits the spatial resolution with which the material can be studied. Reflectometry is also of interest in biophysics for the determination of the structure of complex molecules.

Ultra-cold neutrons allow probing the surface transition region with potentially much improved spatial resolution. Because existing facilities only provide low densities of ultra-cold neutrons, their use is not yet widely spread. Experiments that require beams of ultracold neutrons (e.g., measurement of the electric dipole moment of the neutron) can be done only at reactors, while experiments that need bottled ultracold neutrons (e.g., measurement of the neutron lifetime) could make effective use of the peak flux of an accelerator-driven spallation source. New approaches of producing ultra cold neutrons at spallation neutron sources are being developed.

Tritium Production

A spallation source with a 100 MW beam (three orders of magnitude beyond ISIS) would match the time-averaged flux of a large reactor (such as the Department of Energy's Advanced Test Reactor) and could be used for tasks, such as isotope production and materials irradiation testing, that rely entirely on integrated flux (fluence). Such a machine has been proposed, and is being considered, for the production of tritium (through capture of thermalized neutrons in helium-3 or lithium-6 targets). Tritium is an essential ingredient of thermonuclear weapons which decays away with a half-life of 12 years. It must therefore be continuously replenished if the US wishes to maintain a stockpile of thermonuclear weapons. The envisaged accelerator tritium production facility would offer inherently safer and more flexible production and have greatly reduced waste disposal problems than existing or proposed reactor based facilities.

Transmutation and Fission Energy

Another possible application of national relevance for a high-intensity spallation driver is the burning of actinide waste and surplus plutonium in subcritical reactor assemblies. By converting long-lived radioactive waste into short-lived or even stable isotopes one may be able to avoid the politically and socially complex problem of long-term storage of radioactive waste. Short-term storage would be sufficient for the transmuted end products because most of them would decay into stable nuclides within a time span measured in decades rather than millennia. The technique appears attractive, but more research is needed to ascertain its effectiveness. In addition, the highly complex issue of its cost and benefit as compared to the alternative long-term storage solution must be carefully considered.

Accelerator-driven fission reactor assemblies are also under discussion for the generation of nuclear energy. They could operate with subcritical amounts of fissionable material since the driver would provide the necessary neutrons without need for a self-sustaining chain reaction. Serious accidents due to run-away reactions (as, for example, the core-meltdown of the Chernobyl reactor) are then impossible because operation of the plant requires the neutrons generated by the accelerator-driven spallation source. When the accelerator is turned off, energy (and thus heat) production by fission stops virtually instantaneously. Since such reactors would largely burn their own waste into short-lived radioactive remnants, they can be operated at a much reduced environmental cost. Moreover, such reactors can utilize the thorium-uranium cycle which does not require reprocessing of fuel elements with its associated risk of diversion of weapons grade material. Such reactors could thus greatly reduce the risk of nuclear weapons proliferation.

Concluding Remarks

Nuclear science research has made possible many beneficial applications in society. In some well established cases, such as nuclear magnetic resonance imaging – now simply called "magnetic resonance imaging" (MRI), the nuclear and atomic physics roots are nearly forgotten, except for the recent use of (nuclear) spin-polarized rare gases. More recent applications, such as microprobe beams or accelerator mass spectrometry (AMS), were developed at nuclear physics research facilities. As these techniques provide ever more sophisticated solutions to previously intractable problems, dedicated (and hence more cost-effective) accelerators are being designed and built. Nuclear medicine has become an important component in the Nation's health care system with new imaging technologies and cancer treatments still being developed by teams of nuclear and medical scientists. Sophisticated and highly sensitive nuclear detection methods make important contributions to our Nation's security, to the understanding and monitoring of atmospheric and oceanographic circulation patterns, as well as to the early detection of environmental pollution. Many of these applications were only possible because of nuclear science's vibrant and intellectually stimulating research environment which encourages innovative and unconventional approaches and because of its broad technical infrastructure which makes possible swift tests and verifications of new ideas or emerging cross-links between disciplines. As basic nuclear science pushes to explore new frontiers, new and promising applications of nuclear technology will emerge with important impact on the long term issues the Nation must face, lest it give up its world-leading role: high-power free-electron lasers offer environmentally benign manufacturing technologies, high-intensity heavy-ion accelerators could be used as drivers for inertial fusion power plants, and spallation sources driven by high-intensity proton accelerators could provide an alternative and safe source of neutrons to renew the Nation's stock in tritium, to burn (transmute) radioactive waste, or to form the basis for fail-safe and much cleaner nuclear fission power plants. Most important of all are those applications which have not yet been thought of or for which the necessary know-how does not yet exist.

IX. RECOMMENDATIONS AND RESOURCES

This Long Range Plan for Nuclear Science puts forward the nuclear science community's goals and priorities for addressing fundamental questions about the structure and dynamics of strongly interacting matter as we approach and enter the twenty-first century. We anticipate major new opportunities to understand nuclei far from stability, with a significant impact on our understanding of nuclear structure and of astrophysical processes. Studies of the quark structure of matter will elucidate the intertwined issues of quark confinement and nuclear forces. We expect to create and study matter in a "new" high-temperature phase in which the quarks are no longer confined, thereby learning about the evolution of the early universe. And we expect to advance new precision tests of the Standard Model, further constraining and hopefully guiding theoretical constructs which go beyond this highly successful, but incomplete, description of nature's elementary particles and forces. With this intellectual framework, and cognizant of our additional responsibility for educating a new generation of scientists, the Long Range Plan Working Group evaluated priorities and made recommendations within the budgetary framework provided by the agencies.

Recommendations

The last several years have seen substantial development of the tools needed for the major scientific thrusts indicated above. Indeed, as stated in the charge requesting this Long Range Plan, "Nuclear science has made impressive progress since the 1989 Long Range Plan was submitted to the agencies. Significant new capabilities have been realized or are near completion at CEBAF, MIT/Bates, MSU/NSCL, IUCF, BNL, ORNL/RIB, LBL and elsewhere. RHIC is under construction and scheduled for completion in 1999. Major new detectors such as SNO, Gammasphere, Hermes, Borexino, and others will open new horizons in nuclear physics. Also, a vigorous new national Theory Institute has been established." Recently developed instrumentation and upgrades at university-based facilities have also been realized in response to forefront scientific opportunities, thereby sustaining vital university programs with significant educational impact. These substantial investments in people, ideas, instrumentation and facilities will yield significant advances if exploited effectively in the coming years, both through adequate facility utilization and through commensurate support of the scientist and student users.

1. The highest priority for U.S. nuclear science is vigorous pursuit of the scientific opportunities provided by the nation's recent investments in forefront instrumentation and facilities. Scientific, technological and educational returns commensurate with these investments will require resources consistent with those in the charge requesting this Long Range Plan.

The assignment of highest priority to utilization of the array of new tools and facilities is consistent with maximizing return on the investments already made and is clearly important in this time of great pressure on federal resources. If fully utilized, these investments will greatly advance our understanding, at a fundamental level, of the structure and dynamics of strongly interacting matter, of its properties under a wide variety of conditions in the laboratory and in the cosmos, and of the forces that govern its behavior. The Scientific Facilities Utilization Initiative of DOE specifically addresses this recommendation, and its continuance and reinforcement are most important. The recommendation applies *equally* to the very large facilities CEBAF and RHIC (once it begins operation) and to the lower energy facilities, both university and national laboratory based, and detectors which provide essential complements at the nuclear physics frontiers. It entails support for the scientific manpower needed to carry out the experiments, provide the theoretical framework, and educate the next generation through strong university programs. It requires an ongoing level of investment in new instrumentation to meet evolving scientific needs. The funding guidance supplied to NSAC for this Long Range Plan, although substantially more constrained than earlier projections, will permit a productive program. This forward-looking and balanced program has been achieved at the cost of significant and difficult program reductions which have been effected since the 1989 Long Range Plan.

As indicated above, an impressive array of capabilities is now or soon will be available for physics research. Clearly, very large facilities require especially careful planning and sustained commitments. In this regard, completion of CEBAF and the start of RHIC construction represent significant milestones in the NSAC long range planning process. Timely completion and operation of CEBAF was the highest priority in the 1989 Long Range Plan, reflecting the nuclear science community's commitment to a multi-GeV, high intensity, continuous electron beam facility starting with the 1979 Long Range Plan. CEBAF is producing beams of excellent quality and has started its important science program this year. As the world's most powerful "microscope" for probing the electromagnetic structure of nuclei, CEBAF will provide essential data for bridging the hadronic and quark descriptions of nuclear matter. A large user community has invested an enormous effort in the design and construction of experimental apparatus and is ready to do the physics. The laboratory should now be operated at a level commensurate with the investment and the science opportunity. CEBAF's development of superconducting cavity technology has proceeded so well that energies even higher than the design goal of 4 GeV are anticipated in the near term. The community looks forward to further evolutionary increase of the CEBAF energy in the longer term, opening up additional scientific opportunities.

2. RHIC remains our highest construction priority. Its timely completion and operation are of utmost importance for discovery of the quark-gluon plasma and for study of this new form of matter.

The highest priority for new construction in the 1989 Plan was the Relativistic Heavy Ion Collider (RHIC). Its principal goal is to study matter at the highest achievable energy densities in the laboratory, as it existed in early stages of the universe. The transition to deconfined matter, that is, matter in which the quark and gluon constituents of protons, neutrons, and other hadrons are able to propagate over significant distances, is a fundamental prediction of QCD. Establishing this transition will represent a major step in scientific exploration of the world about us. RHIC construction is now well advanced and is on schedule for a 1999 completion date. The unique opportunities to discover and study new phenomena at RHIC have led to the formation of vigorous international collaborations whose members have invested major efforts and funds into the design and construction of advanced detectors suited to RHIC's unexplored regime of ultrarelativistic heavy ion collisions.

To discover and characterize fully the properties and behavior of the quark-gluon plasma, measurement of a large number of complementary signatures is essential. Selected additions to the large RHIC detectors will substantially enhance their capability and should be implemented in a timely fashion.

Initiatives

A number of facility initiatives and upgrades that would greatly enhance U.S. capabilities in nuclear science have been proposed. Within the financial boundaries of our charge (discussed below), we recommend selected initiatives in the areas of radioactive beams and hadron beams.

The ability to create nuclei at the limits of stability has generated intense world-wide interest. Near these limits, new regularities are anticipated that will profoundly influence our understanding of nuclear structure and the symmetries governing nuclear behavior. First-generation programs of limited scope are being pursued in the U.S., adding to the widespread interest. New capabilities would allow a robust program of nuclear structure studies in a new domain that is also central to understanding the stellar processes through which the elements were synthesized.

3. The scientific opportunities made available by world-class radioactive beams are extremely compelling and merit very high priority. The U.S. is well-positioned for a leadership role in this important area; accordingly

• We strongly recommend the immediate upgrade of the MSU facility to provide intense beams of radioactive nuclei via fragmentation.

• We strongly recommend development of a cost-effective plan for a next generation ISOL-type facility and its construction when RHIC construction is substantially complete.

The fragmentation and Isotope Separator On-Line (ISOL) techniques are complementary in the species and energies of the beams produced. Thus, they drive different facets of the science. The MSU upgrade can be accomplished on a relatively short time-scale. Construction of a major ISOL-type facility is estimated to cost somewhat more than a hundred million dollars and thus, within the constraints of our charge, must wait several years, until RHIC construction is substantially completed, for the bulk of its funding.

Proton beams, and the secondary beams of neutrons, mesons and leptons provided by intense primary beams, are a major part of the arsenal for nuclear science. The community has experienced significant loss of opportunity in this regard with the closure of LAMPF as a nuclear physics user facility and with the Canadian decision not to proceed with construction of the proposed large facility, KAON. On the positive side, significant new capabilities with electromagnetic probes will address related physics, selected experiments with intermediate energy pion and lepton beams will be possible, the technology for polarizing protons in storage rings has been developed and utilized effectively, and the intensity of kaon beams at the Brookhaven AGS has been increased significantly. These developments lead to important scientific opportunities with hadronic beams, which build on existing facilities and experience and also lead to a new direction.

4. Multi-GeV proton beams are an essential tool for forefront studies aimed at elucidating the quark structure of nucleons and nuclei.

• We strongly recommend funding for LISS as a major NSF research equipment initiative. This facility will build on IUCF's leadership in stored, cooled, polarized proton beam technology to enable innovative experiments addressing the short-range behavior of nuclear forces.

• The RHIC/AGS complex, in addition to its core heavy ion program, will offer significant capabilities with hadron beams. In particular, the collisions of polarized proton beams in RHIC will enable unique studies of quark and gluon distributions inside the nucleon. These studies are important for understanding hadron structure and should be pursued.

Polarized proton interactions in the multi-GeV energy regime have been recognized as an important probe in unraveling the nature of the short-range force between nucleons and in obtaining new insights into quark and gluon distributions in the nucleon. These two facilities provide unique capabilities.

Recent advances in accelerator technology for producing appropriate beams in storage rings, principally at Indiana, provide the basis for LISS, a cooler ring that would provide 15 GeV beams of exceptional quality. Construction would require approval as an NSF major research equipment initiative, helped by substantial local matching funds.

Polarized protons in RHIC could be collided at total energies as high as 500 GeV. These studies would be of interest to both nuclear and high energy physicists and would require modest incremental operating costs. The RHIC spin program has elicited significant international contribution and would be scheduled around the RHIC heavy ion program. In addition, when the AGS is not being used as an injector for RHIC, extracted beams could be made available for specific experiments on the basis of scientific merit; for example, the study of hypernuclei could be pursued with greatly improved capabilities.

Instrumentation

While the last three recommendations have focused on facilities, there are substantive infrastructure issues that must be addressed in order to pursue our first priority, that of capitalizing scientifically on the investment in frontier opportunities. Instrumentation initiatives of modest scale are at the core of forefront scientific investigation and of student education.

A varied menu of important opportunities already exists, with many scientists strongly committed to their realization. These span the major scientific thrust areas described above. Some are ready for implementation, others require more development and design. For example, the cost-effective use by nuclear physicists of accelerators operated by other disciplines (such as Fermilab and SLAC) for experiments probing the quark structure of matter often requires new instrumentation. Selected additions to the RHIC detectors will substantially enhance their capabilities. Large acceptance detectors at the intermediate-energy electron facilities will yield a unique internal target program and new parity-violating scattering experiments. At low energies, a novel approach to coincidence detection of multiple gamma rays can significantly advance nuclear structure studies with highly deformed nuclei. The potential exists for a world-leading ultracold neutron source for precision tests of the Standard Model. Novel techniques for trapping ions and neutral atoms for studies of fundamental symmetries are being advanced at low-energy accelerator facilities in both university and national laboratory environments. While instrumentation tends to be thought of as focussing on experimental efforts, the theoretical community sees a need to substantially increase computing power to address problems ranging from nuclear structure to first principles calculations in QCD. These and other innovative instrumentation proposals are coming forward regularly to capitalize on scientific, technical and facility progress. It is essential to allow flexibility to respond to the most important proposals through the peer review process. This is an important component of our first recommendation concerning vigorous pursuit of scientific opportunity.

5. We recommend an increase in equipment funding.

Innovative projects addressing key issues in all of the major scientific thrust areas, and of moderate cost, are causing intense pressure on these funds at the current level. Such projects often contribute significantly to education and to university technical infrastructure.

Theory

We have noted that our science is based on observation and measurement, so the recommendations above largely focus on provision of the necessary experimental tools. However, significant progress depends crucially on the partnerships and synergy between experiment and theory. For example, new techniques have greatly increased the precision of microscopic nuclear structure calculations; continuing progress will be needed as forefront experimental tools (such as radioactive beams) explore new domains of nuclear structure and dynamics. CEBAF and RHIC, as well as other new capabilities, will address core issues concerning the quark structure of matter and quark deconfinement; increased theoretical understanding of the observable consequences of novel phenomena in QCD will be an important guide to experiment. The wealth of scientific challenges, including the significant intersections with astrophysics and particle physics, pushes the theoretical community towards new problems and demands expanding expertise.

6. A strong nuclear theory effort is essential for continued progress at the emerging frontiers of nuclear science. We recommend continued strengthening of the theory program.

An important and succesful initiative has been the Institute for Nuclear Theory at Seattle, established in 1990, which has had a stimulating effect in establishing new directions, forging new collaborations, and fostering theoretical progress in support of major experimental programs.

International Collaboration

International cooperation in nuclear physics has become and will continue to be extremely lively and productive at the scientist-to-scientist level. With the increased scale of major facilities, a number of more formal cooperative agreements have been pursued to open up scientific opportunities for the international community at unique facilities. In turn, these facilities have been able to extend their scientific reach through instrumentation development by the international partners. Current examples include, among many others, the important detector contributions by European and Japanese scientists to CEBAF and RHIC in the U.S., and U.S. participation in the Sudbury Neutrino Observatory (SNO) in Canada, in the HERMES program at the DESY/HERA facility in Germany, and in CERN programs with muons, antiprotons and heavy ions.

To further this process and to help lay the groundwork for extended collaboration, NSAC invited representatives of the Nuclear Physics European Collaboration Committee (NuPECC) and of the Steering Committee of the Japanese Society of Nuclear Physics as official observers and participants in our Long Range Plan meeting. The observers provided overviews of the programs and plans in Europe and Japan and, most importantly, took part in the scientific discussion leading to our recommendations. These exchanges were very important to the Long Range Plan Working Group, pointing out the complementarity of existing facilities and areas of mutual interest for new thrusts. The importance of continuing dialogue among the scientific communities, including early discussion of major facility initiatives (for example, building on the worldwide interest in radioactive beams), is apparent. To help address these issues, the International Union of Pure and Applied Physics has recently created a Working Group for International Collaboration in Nuclear Physics. The function of this body is (in part) to report on the status of nuclear physics and new scientific directions, to identify new opportunities in pure and applied nuclear physics and to facilitate access to and utilization of existing and future international facilities.

Beyond this, linking the scientific discussion with the planning activities of responsible government officials should be encouraged. The LRP process in the U.S. has been effective largely because it represents a long-standing continuing dialogue between the research community and the government on scientific priorities and recommendations for implementation. Extending this principle to an international context will help guarantee that the appropriate tools are available to the worldwide community for the highest priority science in the face of constrained resources.

7. We recommend that dialogue and collaboration among the major international nuclear science communities, and most specifically discussion among their representative advisory committees, be continued and extended. These discussions should provide input to the nuclear science planning activities of the governments supporting these research communities.

Education and Outreach

Education of the next generation of scientists is a very important corollary of fundamental research, and the nuclear science community contributes substantially in this area. Nuclear physics research annually yields more than one-eighth of the nation's Ph.D.'s awarded in physics. Regardless of the exact career paths followed by these individuals, they collectively possess nuclear science and technology competencies which are a critical element in our national workforce. The majority of these young scientists establish careers in industry and national laboratories, pursuing the nation's strategic goals with the special combination of skills and problem-solving experiences developed in forefront nuclear science research. Many embark on teaching careers, at research universities and elsewhere. A significant number work in the health professions and in government. Even with recent changes in the scientific job market, these young scientists continue to find opportunity for a broad range of satisfying career paths which help advance the nation, and we anticipate an approximately constant level of graduate training within the framework of the Long Range Plan charge of an overall constant level of effort. Predictability of funding over a several year time period is essential for sustaining an appropriate level of graduate training.

In addition, nuclear physicists contribute to broadening the overall education of undergraduates by offering them opportunities to participate in challenging research projects. This is often a defining experience, since entirely new talents are developed in the pursuit of new knowledge as opposed to the classroom experience of gaining accumulated knowledge. While this is true throughout forefront science, nuclear physics offers some special opportunities for undergraduates, such as on-campus accelerator environments and collaboration in research teams. A number of particularly successful sites in the NSF's Research Experiences for Undergraduates (REU) Program are associated with on-campus accelerator facilities. The REU program provides undergraduate students, many from smaller colleges without research facilities, an opportunity to participate in summer research under the guidance of a faculty mentor. The extensive support of such programs by nuclear scientists has expanded considerably the scope of science and engineering curricula. It also provides motivation for sustaining and improving the university technical infrastructure for nuclear physics.

A second important corollary of fundamental research is use of the unique assets of the research enterprise to improve public scientific and technical literacy. Nuclear physicists are very active in programs that strengthen pre-college science and mathematics education. Many of the programs have a focus of increased participation by women and underrepresented minorities. Increasingly, NSF and DOE are supporting such outreach activities as natural extensions of their research programs. We strongly support such recognition of these activities as part of the responsibility of our research community. One example of the coherence among research and educational commitments is provided by the developments at and around CEBAF. The new scientific opportunities there have stimulated the creation of more than seventy faculty positions in the southeast, the development of new Ph.D. programs at historically black universities, the expansion of undergraduate research at predominantly minority institutions, and the participation of about 10,000 grade school children in week-long science programs. The development of outreach programs by many university-based groups and facilities contributes effectively to increasing the public awareness of science.

8. We urge that the funding agencies sustain and indeed strengthen their support for the efforts of the nuclear science research community in making effective use of its unique facilities and experience to enhance science education, improve public scientific literacy, and expand further its outreach activities from grade school to graduate school.

Applications

Nuclear physics techniques have provided important tools for many disciplines in science and technology, and nuclear scientists continue to find new and original ways to meet societal needs. These new technologies have contributed substantially to the national interest in the areas of health, economic growth, environmental protection, and national security. As one example, nuclear isotopes, accelerator technology and imaging techniques have changed medicine, with nuclear medicine departments now in thousands of hospitals performing many millions of procedures annually. Both non-invasive diagnosis and clinical treatment programs are encompassed, and new developments promise important advances in both areas. Many more examples of important societal applications of nuclear science and technology are provided in the body of the Plan. In addition to the direct benefits, we view interdisciplinary research and the extension of nuclear science technology developments towards well-chosen applications as significantly enriching the environment for graduate education and undergraduate research.

9. We support increased opportunity for interdisciplinary research and for initiating promising applications of nuclear science and technology towards societal goals.

Resources

NSAC received from the agencies explicit budgetary guidance for this Long Range Plan. For the Department of Energy, our Plan corresponds to a FY 1997 budget between $325M and $350M and then goes forward at a constant level of effort (interpreted as constant spending power). The high end of the charge corresponds to the FY 1995 budget adjusted for inflation; the low end corresponds to a 7% reduction from the FY95 budget, adjusted for inflation. For the National Science Foundation, the charge specifies constant level of effort starting from the FY 1994 budget of $42.2M. This would require an increase in the FY97 NSF budget of 11% relative to FY95.

Since the issuance of the Interim Report in April 1995, significant concerns about the budgets for both agencies have arisen. It was assumed that FY 1996 budgets would provide for a "reasonable transition" between the FY95 budgets and the budget guidance for FY97 from the agencies. As is detailed below, this is not the case. In terms of spending power, the budgets for both agencies are down by nearly 20% from the actual levels of a few years ago. This has forced termination of scientifically productive programs in order to sustain a balanced program with reasonably healthy components. Two NSF-supported university accelerators are no longer funded; others now receive reduced support. The two largest DOE-supported nuclear science facilities at the time of the 1989 LRP, the Bevalac and LAMPF, have ceased to operate as nuclear physics user facilities in large part to permit development of CEBAF and RHIC. This process of providing new forefront capabilities balanced by orderly program reductions has sustained a world-leading nuclear science program within financial constraints, but the recent drop in funding has put extraordinary pressure on the program.

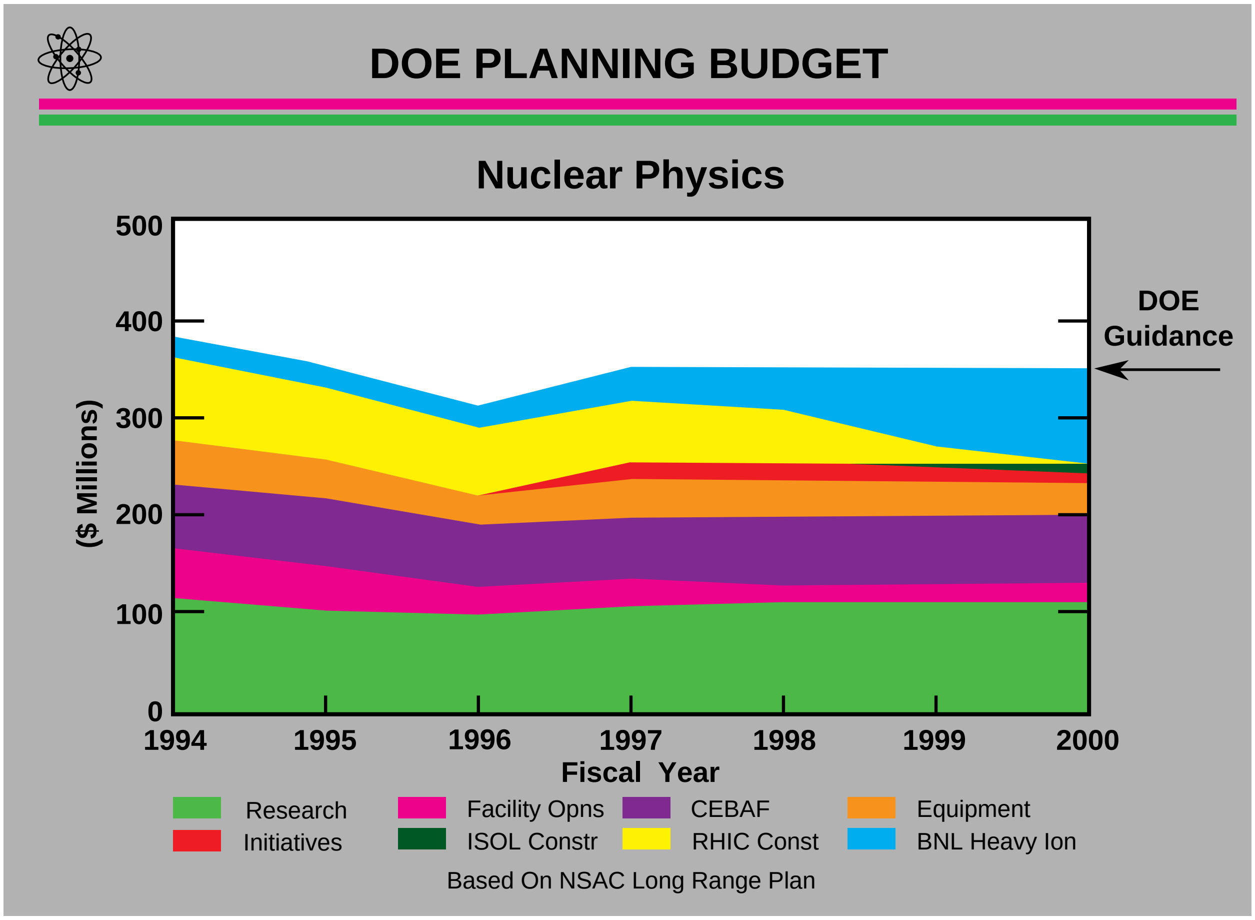

Figure IX.1: DOE Nuclear Physics Budget Profile in FY 1997 Dollars. See text for full explanation. "Research" includes both experimental and theoretical research at universities and at national laboratories, but excludes CEBAF activities and Brookhaven heavy ion research activities. "Facility Opns" includes accelerator facility operating costs except for CEBAF and Brookhaven. "CEBAF" entry includes the end of construction funding through FY94, facility operations, and in-house research. "Equipment" includes capital equipment, accelerator improvement, and general plant projects. "Initiatives" and "ISOL Constr" are initiatives explained in the text. "RHIC Const" is funding for construction of RHIC. "BNL Heavy Ion" includes AGS and RHIC operations and in-house heavy ion research. Inflator/deflator to FY97 taken as 3% per year.

Department of Energy

The recommended budget profile for the DOE nuclear physics budget is shown in Figure IX.1. It conforms to the higher level budget guidance provided by the charge, namely, $350M in FY 1997 and constant level of effort thereafter. Notice that this budget represents a constant level of effort from FY 1995.

Our highest priority is vigorous pursuit of the science opened up by recent investments in facilities and instrumentation. This is reflected in Figure IX.1 in the Research, Operations and CEBAF profiles. The Research recommendation calls for a small increase, focused on university programs. This will have considerable leverage in providing adequate resources for university-based scientists, particularly young faculty, both to carry out their science in a timely way and to extend student participation in research. For operation of user facilities, including CEBAF, the recommendation calls for constant buying power. It is essential to recognize that this is contingent upon the higher of the FY97 budgets specified in the charge, which minimally provides for cost-effective and scientifically effective utilization of operating facilities.

Our recommendations call for strengthened instrumentation funding and for some new initiatives. This is reflected in Figure IX.1 by the Equipment, Initiatives and ISOL Construction profiles. Base Equipment funding, which continues to provide very important new capabilities (such as SNO and Gammasphere), is kept approximately constant in order to retain, for the long term, some flexibility to respond to innovative proposals. Beyond this, Initiatives funding, which contains a strong instrumentation component, is needed to enhance greatly the scientific, technological and educational returns on the nuclear science investment. As noted in Recommendation 5, the pressure on instrumentation funding is intense at this time. Without the Initiatives funding, the selected additions to the RHIC detectors to substantially enhance their capability for discovering and characterizing the quark-gluon plasma would be jeopardized; also under stress would be the needed infrastructure revitalization at universities and laboratories as well as the important effort to strengthen Theory, including the provision of improved computing resources needed to meet the new scientific challenges. R&D funding will permit timely development of a cost-effective plan for a next generation ISOL facility, with construction to start when RHIC is substantially complete. Other examples of highly leveraged initiatives are detailed in the body of the LRP. The Initiatives funding will permit a significant and timely response to those needs.

Our highest construction priority is timely completion of RHIC. The budget profile shows RHIC construction funding ending in FY99, in agreement with current plans, and operations starting in that year. While the exact RHIC operating costs for effective utilization remain to be determined, the amount indicated agrees with the current best estimates and, following in-depth technical review, may be adjusted up or down slightly following NSAC and agency deliberation.

In the lower budget scenario specified in the charge (namely, \$325M in FY97), substantial retrenchments would be necessary. Specifically, in that scenario, we would sustain our recommendation for a small increase in the research budget, leaving the rest of the budget approximately constant. The costs of such a retrenchment would include substantially less utilization of facilities and of other new capabilities. The development of new instrumentation needed to enhance scientific output, including that at the major facilities CEBAF and RHIC, would be highly constrained. If the low funding scenario were to persist, the highly recommended ISOL facility would be stretched out in the absence of a special initiative for incremental funding. Even lower funding scenarios would require re-examination of the carefully constructed nuclear science program and inevitably would lead to a greatly reduced scientific return.

As can be seen in Figure IX.1 there has been a precipitous drop in the DOE budget from FY 1994 through FY 1996. Specifically, the budget, uncorrected for inflation, has dropped from \$349M to \$304.5M in just two years. The effects of this decline have been serious. The LAMPF meson-physics facility has been closed, construction of RHIC has been stretched out and many facilities are operating at reduced levels. At this funding level even the newest facility, CEBAF, cannot be optimally utilized. The budget decrease from FY95 to FY96 is of special concern inasmuch as the \$350M DOE budget guidance would have been constant level of effort from FY95, but translates into a major increase from FY96. Even the \$325M level, which would have been a drop from FY95, represents a significant increase over FY96.

We must stress that the DOE nuclear physics program recommended here results from fifteen years of careful planning to include two major new facilities, CEBAF and RHIC, in addition to the other key science and education activities described earlier. CEBAF is now starting its scientific program, and RHIC is well on its way to completion. Their combined operating cost is nearly half the \$350M budget indicated for our guidance. This does not include support of their user communities whose research was the motivation for constructing the facilities nor the cost of major new experimental equipment as research programs evolve. The \$350M budget is far below that considered realistic at the time of the 1989 Long Range Plan. The FY97 guidance is lower in as-spent dollars than the appropriated amount in FY94 (and also prior years). The agencies and the community have accommodated this through substantial, and painful, retrenchments, while sustaining commitments to the core intellectual framework outlined above. Clearly, in order to support properly the operation of CEBAF and RHIC within a scientifically coherent program, it is essential that the nuclear physics budget hold at or very near the proposed levels. That is, such levels are needed for both cost-effectiveness and scientific effectiveness across the frontiers of nuclear science.

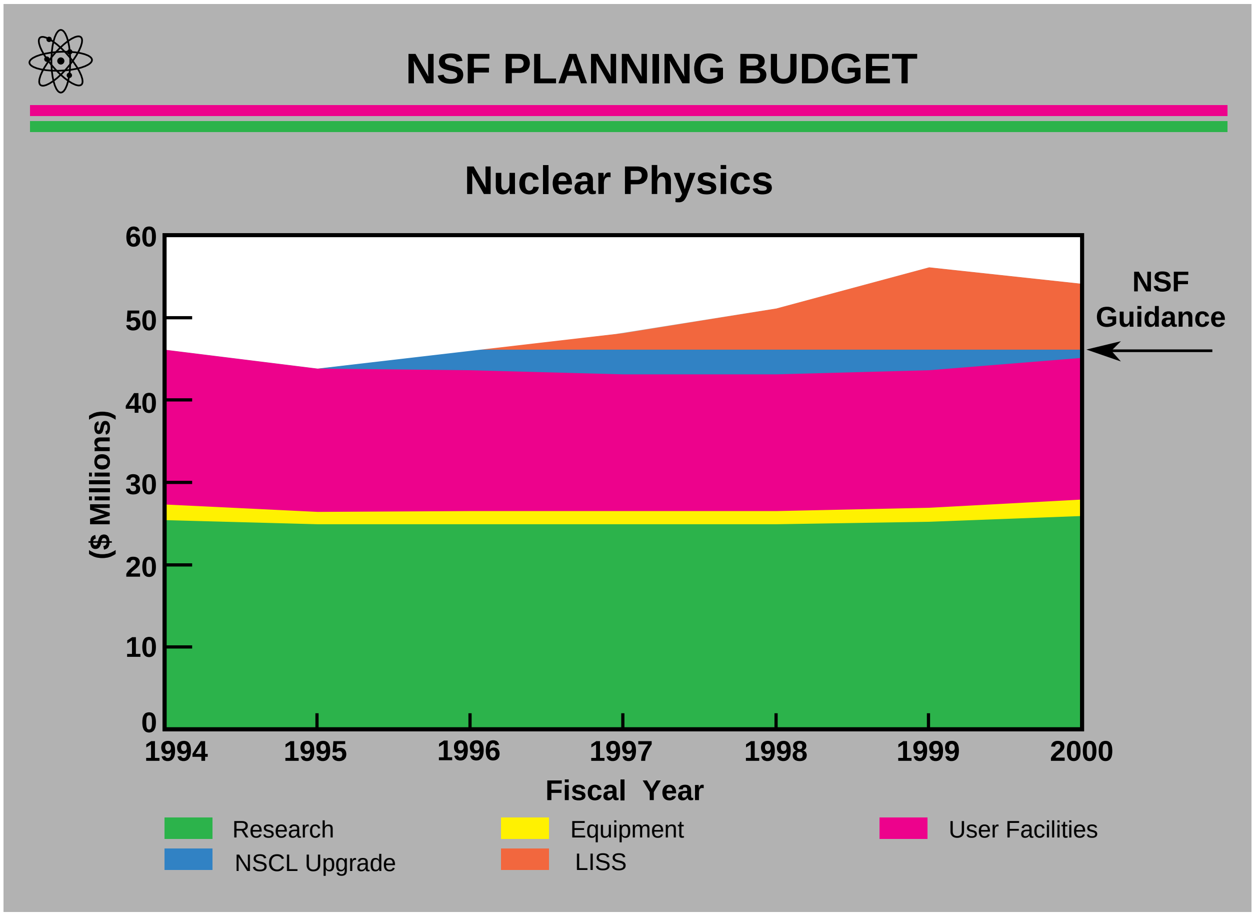

Figure IX.2: NSF Nuclear Physics Budget Profile in FY 1997 Dollars. "Research" includes university-based experiment and theory, together with support of small university-based accelerator laboratories, but not IUCF or MSU/NSCL. "User Facilities" includes both facility operations and research at IUCF and at MSU/NSCL. "Large equipment" includes instrumentation too large to be covered in normal grants. "NSCL Upgrade" and "LISS" are construction initiatives. See text for full explanation. Inflator/deflator to FY97 taken as 3% per year.

National Science Foundation

The recommended budget profile for the NSF nuclear physics budget is shown in Figure IX.2. It conforms to the budget guidance provided by the charge. We stress that, although the NSF nuclear science budget is about one-eighth that of the DOE, this program plays a crucial role. The NSF supports nearly half of the university-based nuclear scientists, and many of those scientists play leading roles at the DOE-supported user facilities. In addition the NSF program supports university-based intermediate energy user facilities, at Indiana and Michigan State Universities, with unique capabilities for proton and heavy ion induced reactions, respectively. In addition, these facilities receive substantial local and state support and have been important centers for accelerator physics research and education.

As with DOE, and for similar reasons, we recommend an increase in the budgets for "Research" and "Large Equipment" over the period of the LRP. The increase in these areas will have a large impact on the conduct of forefront nuclear physics research by university scientists and their students.

Two construction initiatives are recommended, approximately 40% of the cost of which are to be borne locally. One of these, the upgrade of the MSU/NSCL facility (indicated as NSCL upgrade), can be accommodated within the charge. This facility will provide intense beams of radioactive nuclei via fragmentation. This strongly recommended upgrade will create additional pressure on the operating budgets of the user facilities for several years. It should be noted that the NSCL upgrade funding profile does not include an additional $8M of cost-sharing from Michigan State University. The proposed LISS project at IUCF, even with substantial matching funds, has a construction cost well beyond that which can be supported by the NSF nuclear physics program budget (within the constant level of effort scenario of the charge). Therefore, we recommend this very interesting project for consideration in the NSF-wide major research equipment category. Its incremental operating costs are relatively modest but must be carefully planned for in advance of completion in the next decade. The profile shown in Figure IX.2 does not include an additional $20M of cost-sharing from Indiana University.

There are significant concerns with the budget guidance for NSF. Since FY94 there has been a steady erosion of funding so that in order to return to a constant level of effort from that year, as specified in the charge, would require an increase of 11% from FY95 (the FY96 budget has not yet been approved). If the NSF nuclear physics budget is somewhat lower than that specified in the charge (for example, constant level of effort from the FY95 base), the priority for supporting the research and large equipment budgets remains. In such a case, the user facility budgets, including proposed and ongoing upgrades, would experience considerable pressure, resulting in a significant loss of productivity. Since these laboratories play a unique role within American nuclear science for hundreds of scientists, significant underutilization would constitute a major loss to nuclear physics research. Even lower funding scenarios would require re-examination of the balance among program elements and inevitably would lead to greatly reduced scientific returns.

Concluding Remarks

This Long Range Plan for Nuclear Science presents a world-leading program within the budgetary constraints contained in the charge. It is rooted in forefront science and its concomitant contributions to education and technology. It builds upon and extends the earlier Long Range Plans, thereby providing both an appropriate return on the nation's investments in nuclear science and timely realization of major scientific opportunities. It will lead to a much deeper understanding of the strongly interacting matter which makes up most of the visible universe and, in doing so, will train new generations of scientists who will serve the nation in unique and important ways.

The value of the NSAC Long Range Plan process both to the nuclear science community and to the supporting agencies and Congress has been demonstrated repeatedly over many years. It has provided the framework for consensus on major initiatives and difficult priority choices and for the commitment of financial resources and scientific careers. This Long Range Plan renews the process of responsible shaping of the nation's investment in nuclear science through a partnership between the research community and the public.